Higgs @ LHC

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Outline

Introduction

Higgs Phenomenology at the LHC (covered by the talk of R. Harlander)

Experimental Setup (covered by the talks of P. Jenni and C.E. Wulz)

SM Higgs Searches (benchmark analyses)

$H \rightarrow ZZ^*$

$H \rightarrow WW^*$

$H \rightarrow \gamma\gamma$

VBF

$ttH(H \rightarrow bb)$

Additional MSSM Higgs Searches

Example: $H/A \rightarrow \tau^+\tau^-$, $H/A \rightarrow \mu^+\mu^-$

Higgs properties

Mass, couplings, …

Conclusions

Introduction

• The Standard Model of elementary particles answers many of the questions of the structure and stability of matter and is in excellent agreement with all the measurements performed so far.

• The experimental observation however, of one (or several) Higgs bosons will be fundamental to understand the mechanism of electroweak symmetry-breaking and may probe physics beyond the SM

• LHC offers the potential for such a discovery

• There is a very rich variety of search channels for the discovery of the SM Higgs and even more for the non-SM Higgs bosons. An overview **only** of the most relevant channels will be given in this talk

• It must be stated from the beginning that the "all hadronic" states are impossible to separate from the background and very difficult to be triggered

Material used from ATLAS and CMS TDRs unless stated differently.

ATLAS TDR 15, CERN/LHCC 99-15 **CMS TDR 8, CERN/LHCC 2006-021**

ATLAS new sensitivity studies are ongoing

Introduction II

The methodology used in a variety of very different analyses is common in many aspects and can be outlined as following:

- Define the study to be performed based on phenomenological aspects of the procedure

- Find the observables that carry most of the information concerning the particular study

- Optimize the application of the selection criteria using these observables

- Use optimized selection methods that exploit the information carried by the observables *(Usually give better performance but also more dependent on MC)*

- Define the strategy to control systematic uncertainties from the real data themselves

- **Very good understanding of the detector is mandatory**

LHC Environment

p-p collisions √s =14 TeV

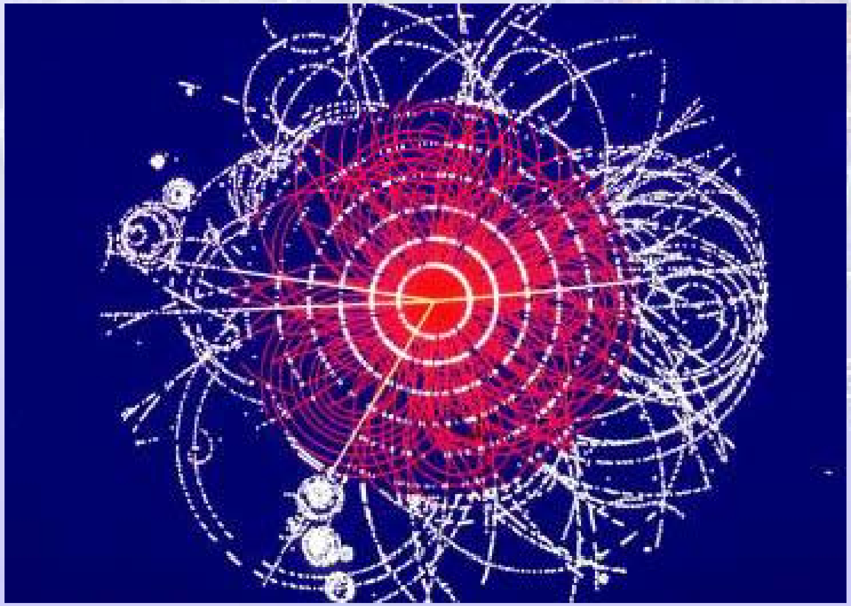
Low luminosity ~$10^{33}cm^{-2}s^{-1}$

~10 fb^{-1} /year

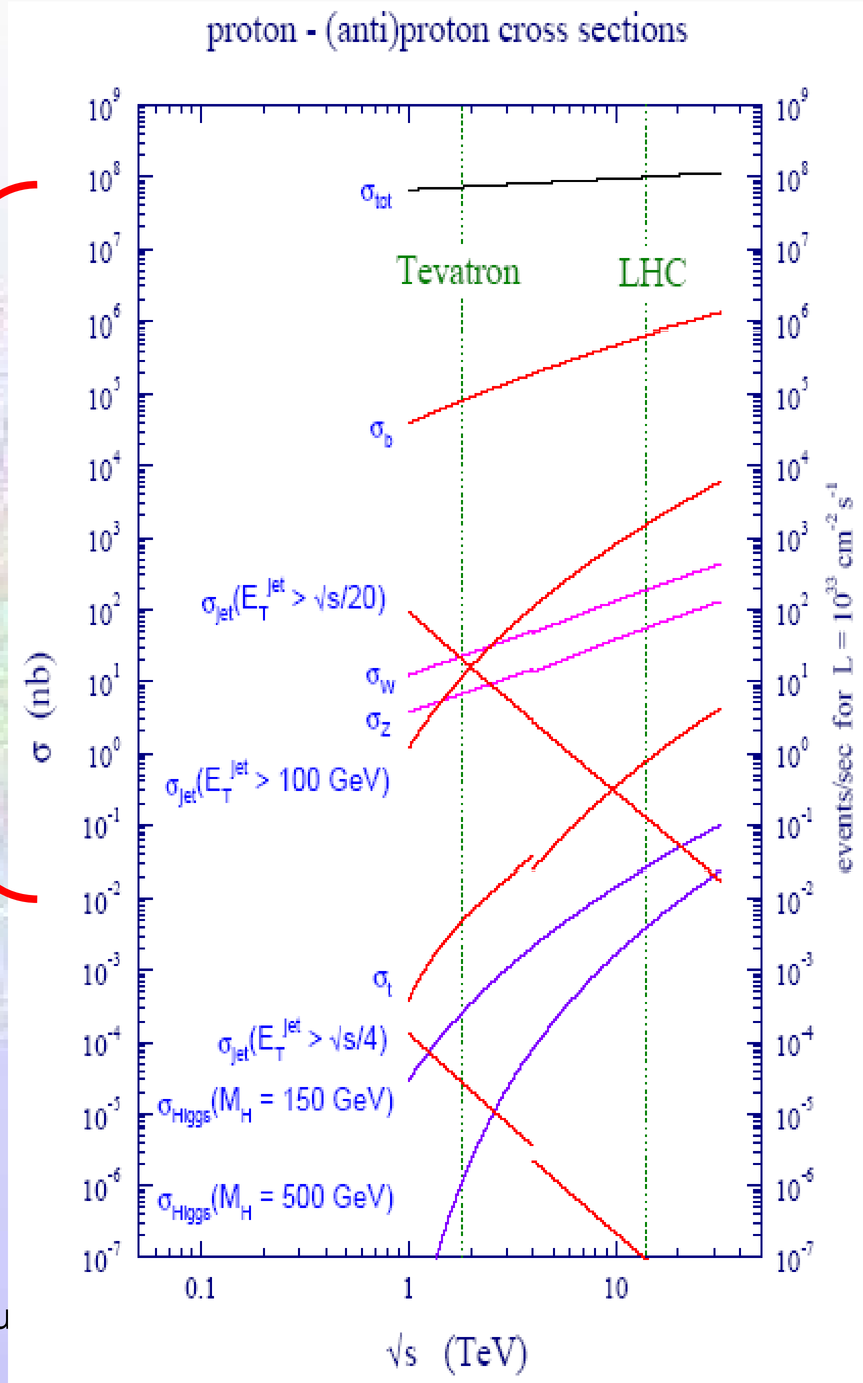
High Luminosity ~$10^{34}cm^{-2}s^{-1}$

~100 fb^{-1} /year

Bunch crossing : 25 ns



10^{10}



Current SM Higgs Limits

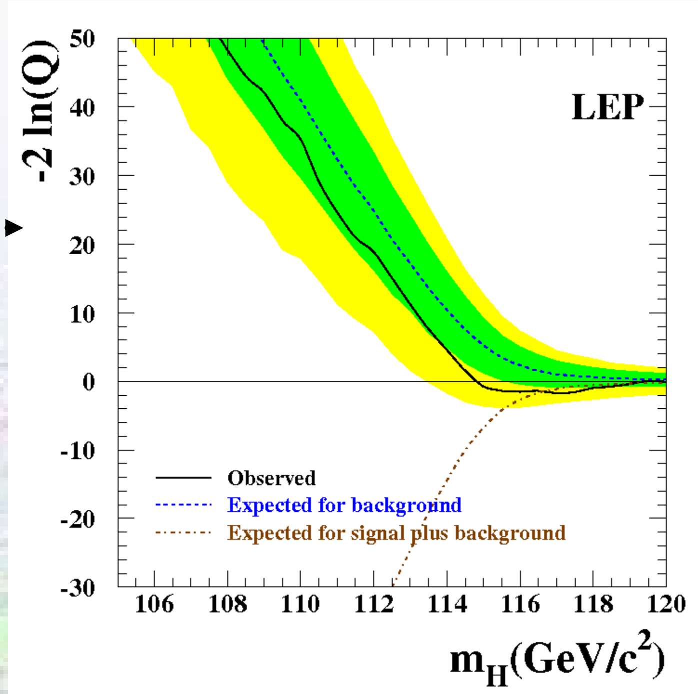
LEP direct search

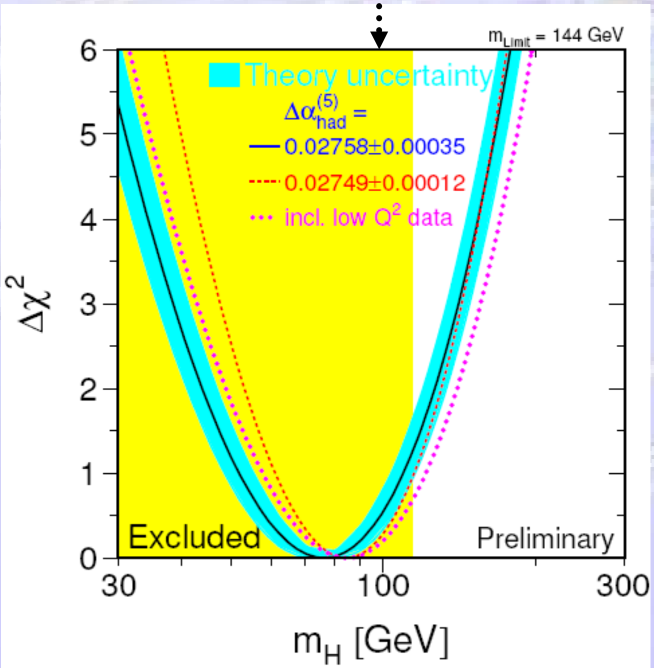
$m_H > 114.4$ GeV @95% CL

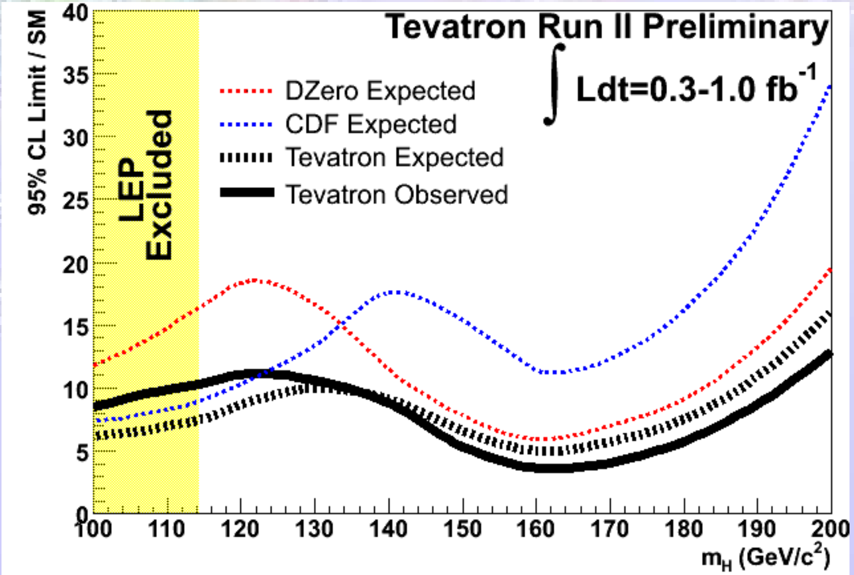
Tevatron Direct search

LEP, SLD, Tevatron e/w fit

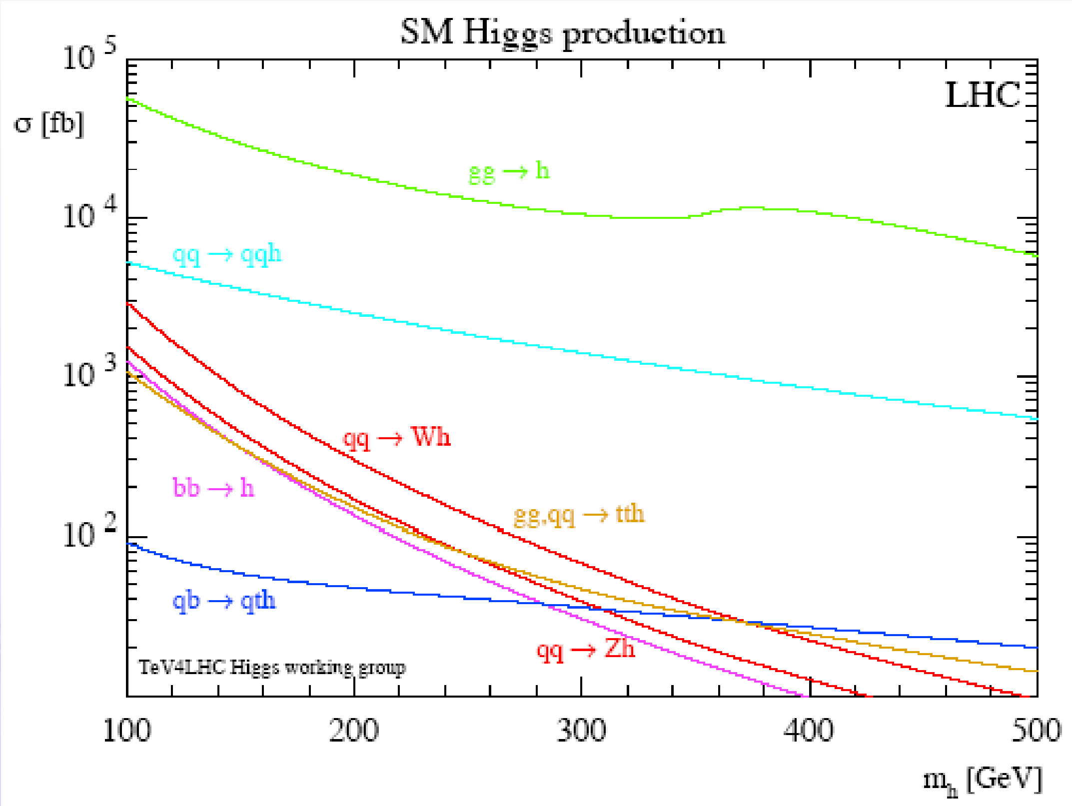
$m_H < 182$ GeV

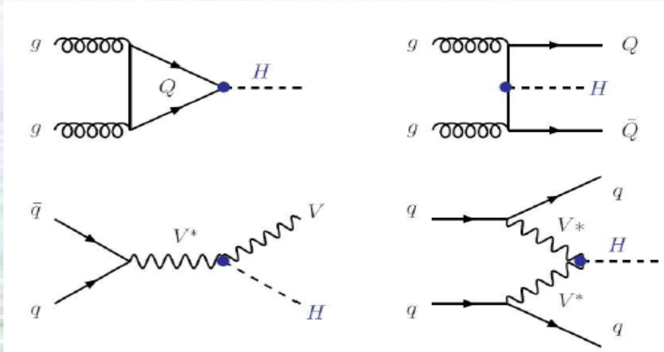






Higgs production at LHC



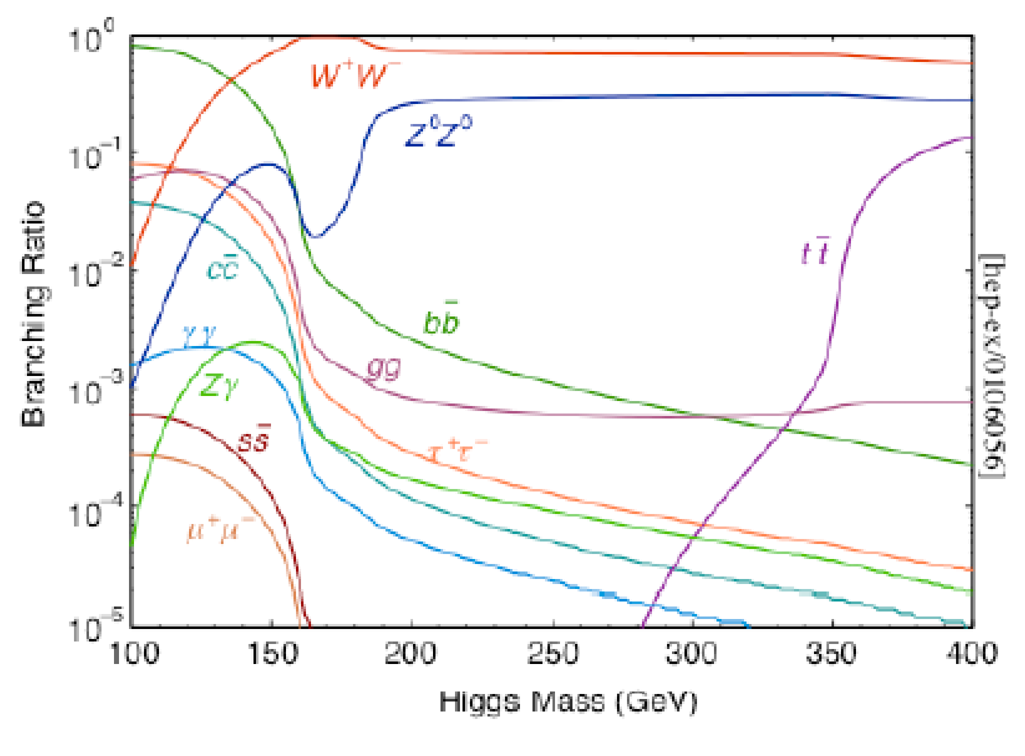


Uncertainties on cross-sections

- gg 10-20 % (NNLO)
- VBF ~ 5% (NLO)
- WH,ZH ~< 5% (NNLO)
- ttH 10-20 % (NLO)

In the Higgs mass range $M_H \sim 100 - 200$ GeV/c^2
gluon fusion cross section is ~ 20 − 60 pb
VBF cross section is ~ 3 − 5 pb
WH,ZH, ttH cross sections ~ 0.2 − 3 pb

Higgs decays



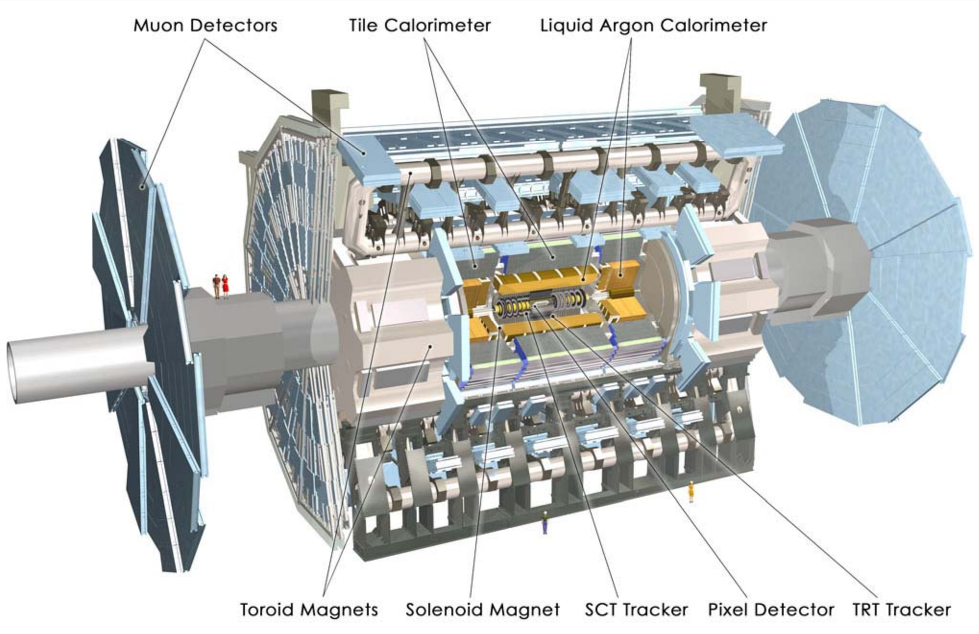
Inclusive search channels:

$H \rightarrow ZZ$ for $m_H \geq 130$ GeV
$\rightarrow 4\,l$
$H \rightarrow WW$ for $m_H \geq 145$ GeV
$\rightarrow l\nu l\nu$
$H \rightarrow \gamma\gamma$ for $m_H \leq 150$ GeV

Exclusive search channels:

VBF $H \rightarrow WW$ for $m_H \geq 115$ GeV
VBF $H \rightarrow \tau\tau$ for $m_H \leq 150$ GeV
ttH with $H \rightarrow bb$ for $m_H \leq 135$ GeV

Uncertainties on branching ratios
few % (NLO)



ATLAS

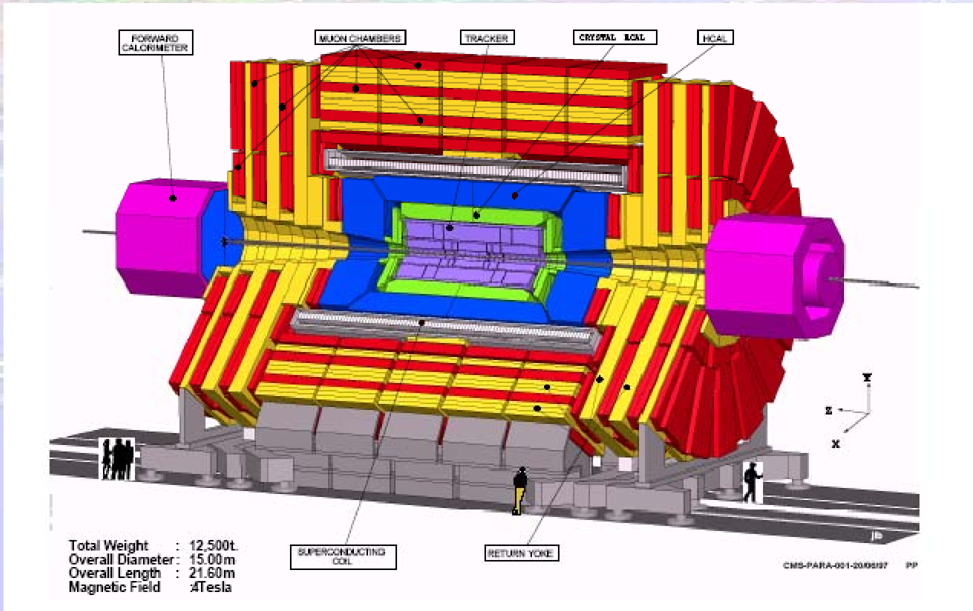
Length : ~45 m
Diameter : ~24 m
Weight : ~ 7,000 tons
Solenoid : 2 T
Air-core toroids

Excellent Standalone Muon Detector

CMS

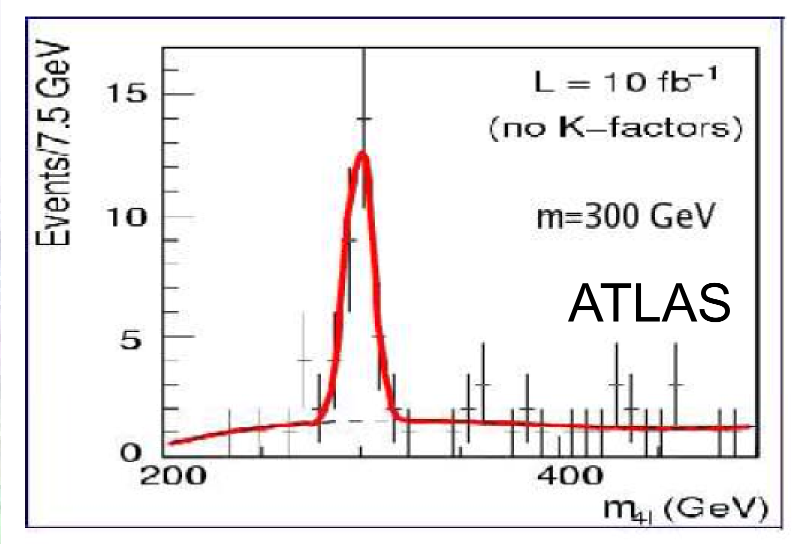
Length : ~22 m
Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T
Compact and modular

Excellent EM Calorimeter

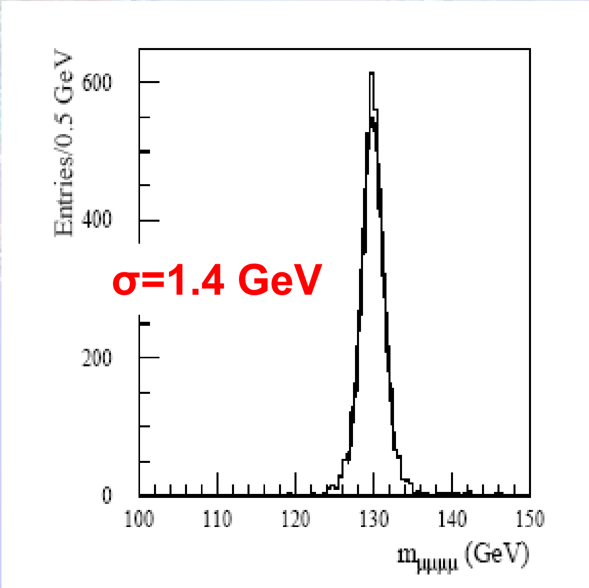


SM Higgs Search $H \rightarrow ZZ(ZZ^*) \rightarrow l^+l^-l^+l^-$

- $ZZ(^*) \rightarrow 4l$ is very clean (also $\rightarrow$ lljj, llνν are studied)
- All H decay products are reconstructed
- Very sensitive for $m_H > 130$ GeV
- **Golden channel** for $m_H > 2m_Z$



Signature:
two opposite sign pair of leptons
coming from the PV
compatible with Z mass (at least 1 couple)



Exploits the excellent e/μ identification and momentum resolution of the detectors

SM Higgs Search $H \to ZZ(ZZ^*) \to l^+l^-l^+l^-$

CMS

Irreducible Background:

continuum $ZZ(^*) \to$4 leptons

Reducible Backgrounds:

Zbb $\to$ 4 leptons

tt $\to$ 4 leptons

suppressed by impact parameter and isolation criteria

gg->ZZ is added as 20% of LO qq->ZZ

ZZ NLO k factor depends on m_{4l}

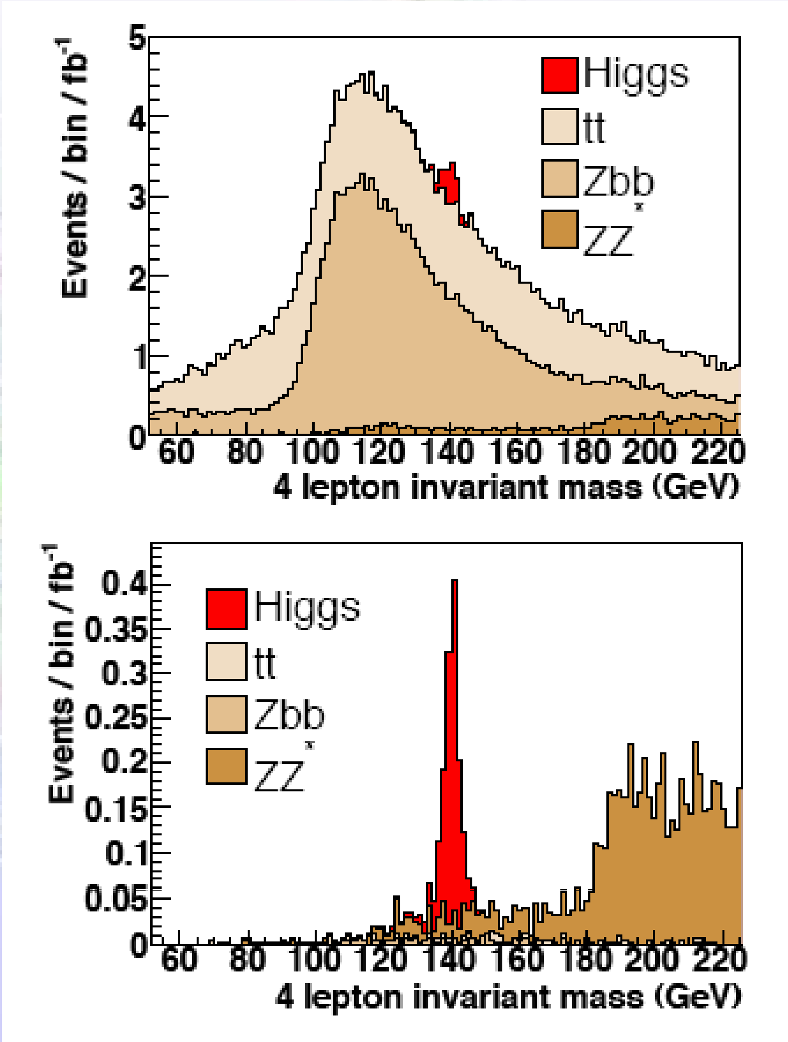
Background control:

a) from side bands

b) from $ZZ \to 4l$ / $Z \to 2l$

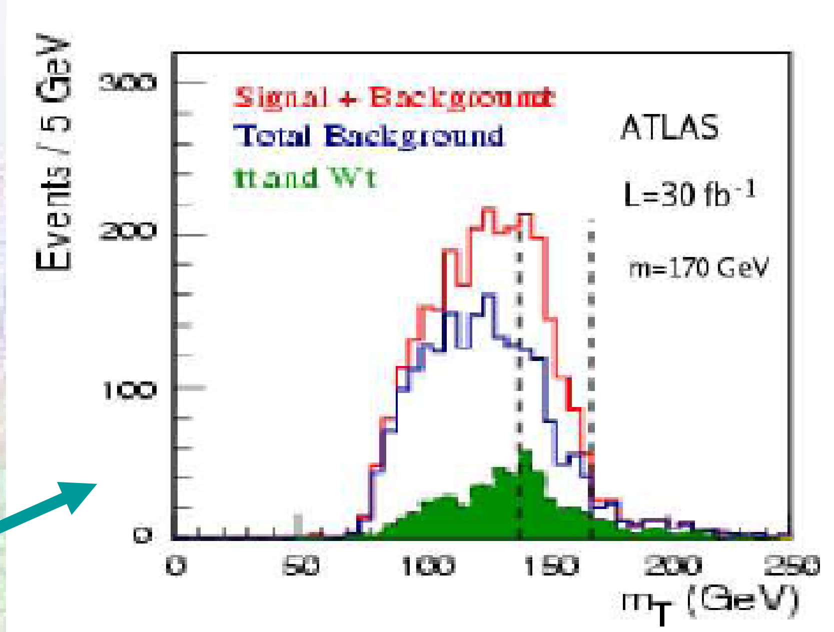
Discovery with less than 10 fb^{-1}

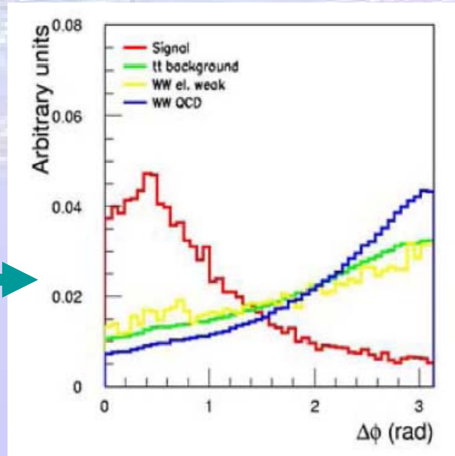
$130 < m_H < 160$ GeV, $2m_Z < m_H < 550$ GeV



SM Higgs Search $H \to WW \to l^+ \nu l^- \nu$

- Important channel for $2m_W < m_H < 2m_Z$
  $H \to WW$ BR ~ 95%
- Exclusive VBF also sensitive in lower mass regions
- Inclusive $H \to WW$ Using dilepton final state
  Signature $l^+ l^-$ and MET
  - no mass peak, have to use transverse mass $l^+ l^- E_{Tmis}$
  - **need to determine shape of background**
  - Lepton anti-correlated
    - W+, W- opposite spin
    - Lepton tend to be close





SM Higgs Search $H \to WW \to l^+ \nu l^- \nu$

Backgrounds:

tt, tWb :

rejected by vetoing the jets

WW,WZ,ZZ:

rejected by kinematical cuts

i.e.

- ETmiss > 50 GeV
- jet veto in η < 2.5
- 30 <pT_{max}<55 GeV
- pT_{min} > 25 GeV
- 12 < m_{ll} < 40 GeV

Background Control

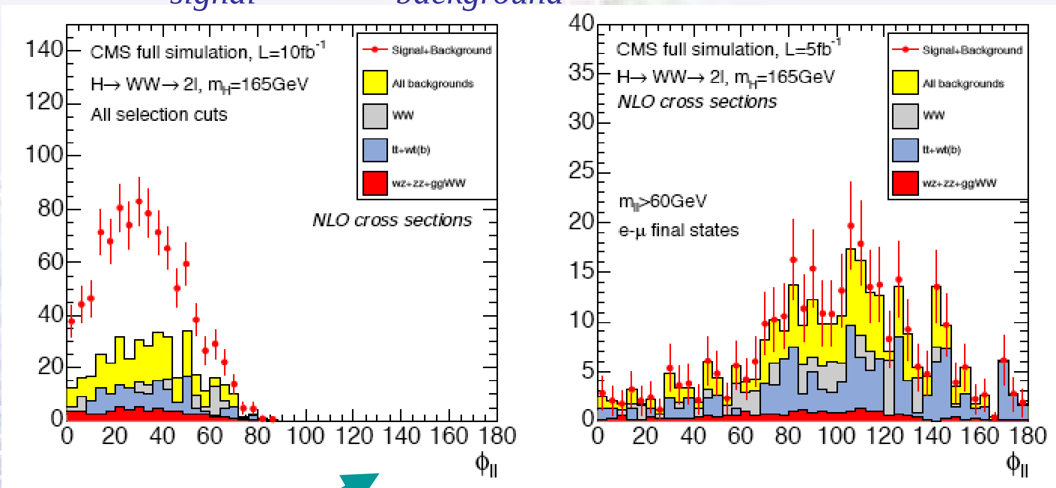
a) Invert cut on l^+l^- proximity

b) Create control samples for tt,WW,WZ

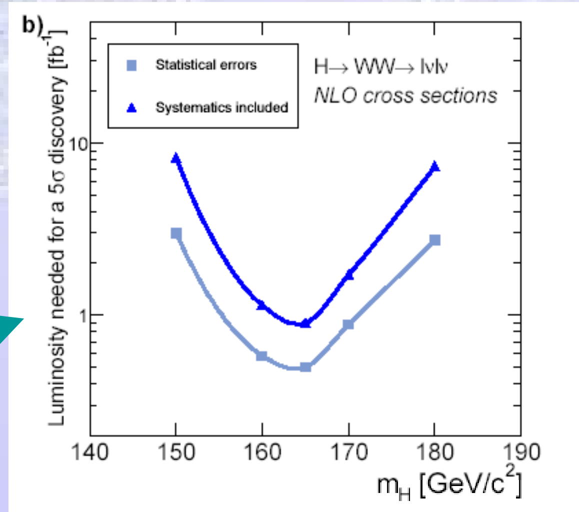
For 1,2 and 10 fb-1 syst err ~19,16 and 11%

NLO σ_{signal} and $\sigma_{background}$

CMS



CMS



Discovery may happen within ~$1fb^{-1}$

SM Higgs Search H→ γγ

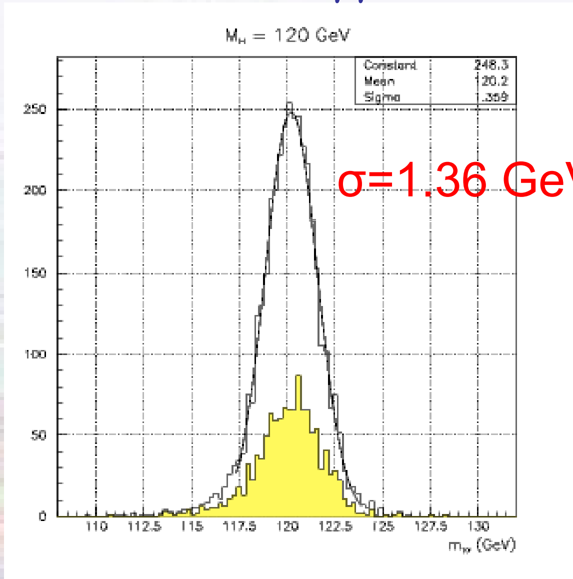
Though H→γγ BR ~ 10^{-3}
Still, very important in the mass range $m_H \leq 150$ GeV
Requires good energy resolution of the em calo

Signature:
2 isolated high Et gammas from PV
Need of excellent energy resolution

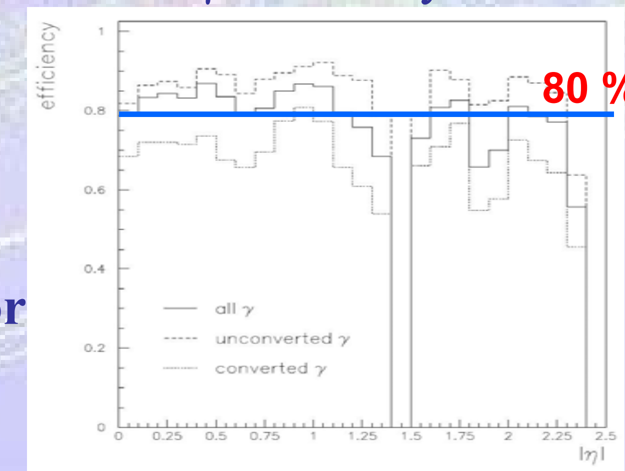
Irreducible Background:
Continuum gamma-gamma

Reducible Backgrounds:
jet-jet and gamma-jet events
Need of
Excellent jet rejection factor
(> 10^3 for 80% γ efficiency)
good π^0 rejection

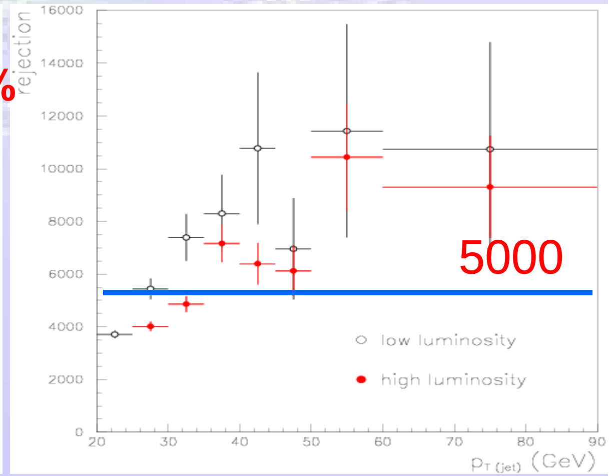
Mass γγ



γ efficiency



Jet rejection



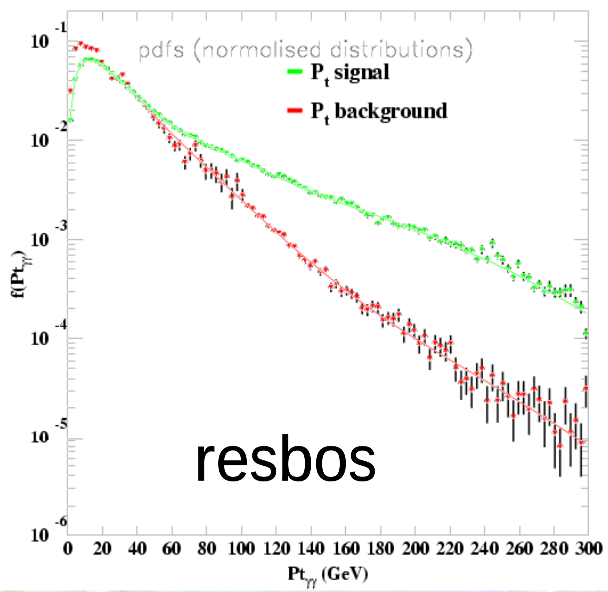
SM Higgs Search H→ γγ

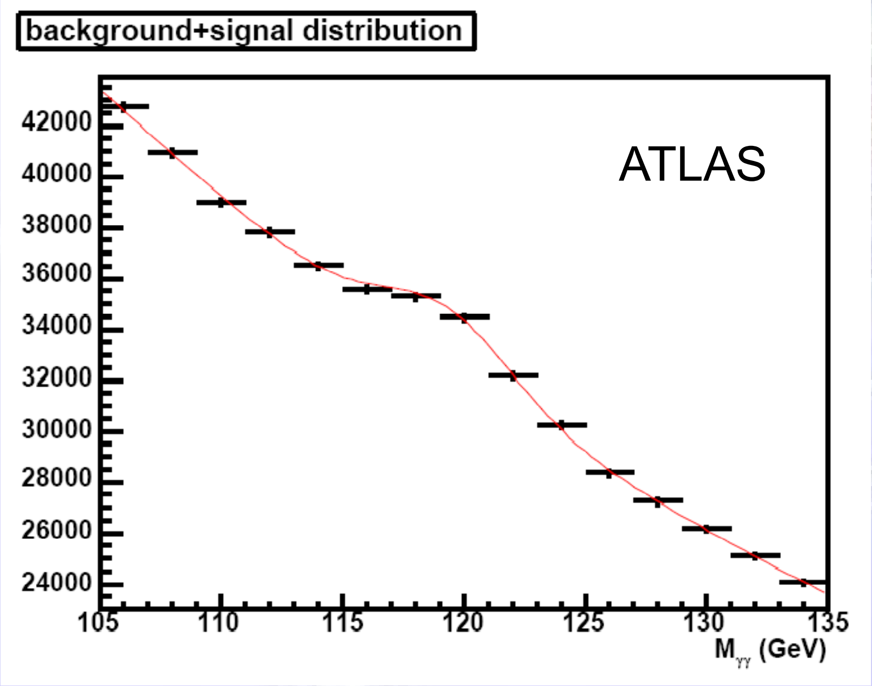
Event Selection

- Kinematical cuts

$p_T^1 > 40$ GeV, $p_T^2 > 25$ GeV, $|\eta| < 2.5$

- Photon identification cuts
- Photon reconstruction and calibration
- Photons direction corrected for PV



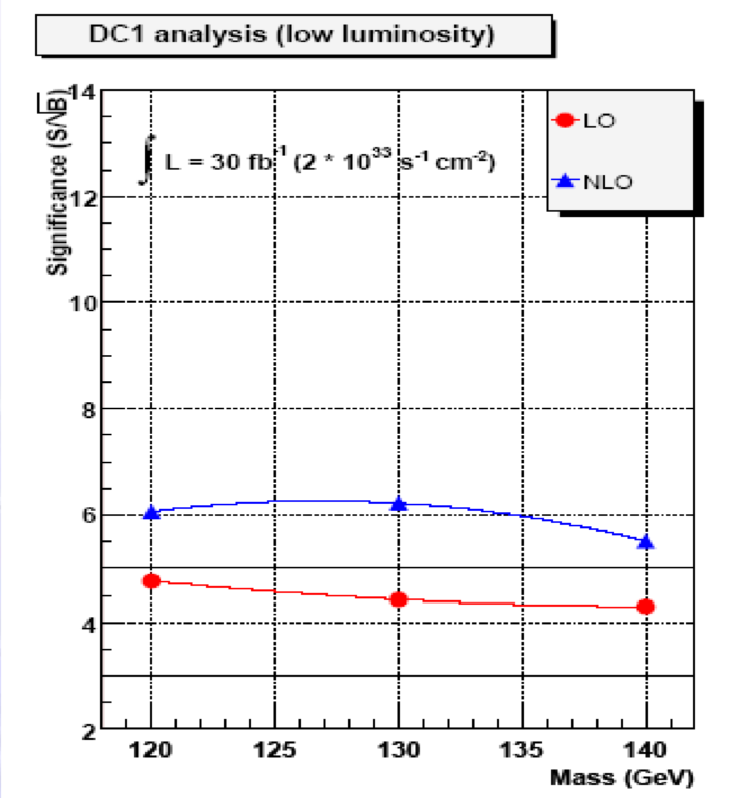


Improve the discovery potential using the shape of kinematical variables

Likelihood ratio method based on kinematical variables of signal and background

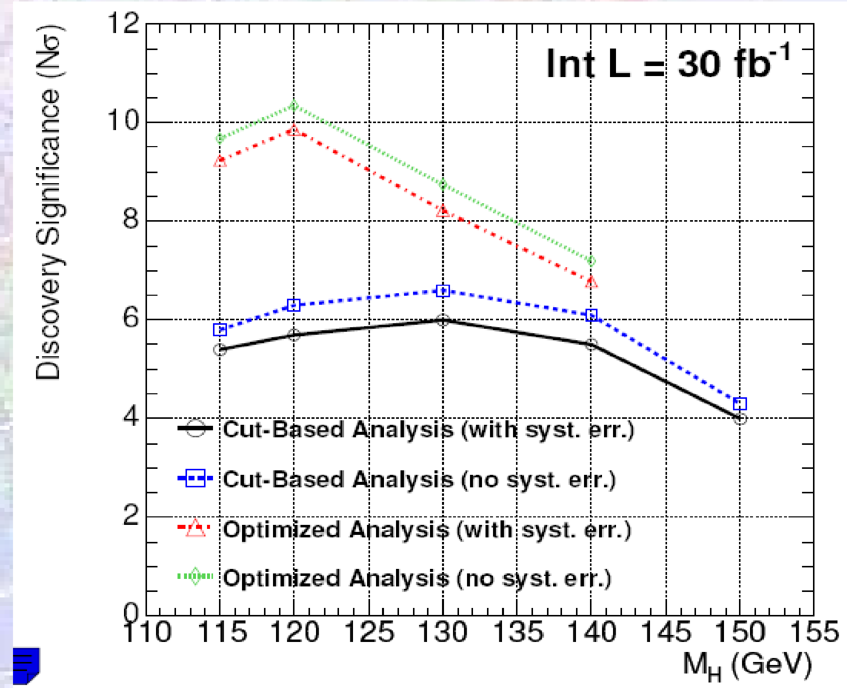
SM Higgs Search H→ γγ

ATLAS
Significance change LO -> NLO



Carminati L., Physics at LHC 2006

CMS
Significance change
with Optimized analysis



R. Kinnunen, 13th Nordic LHC
Physics Workshop 2006

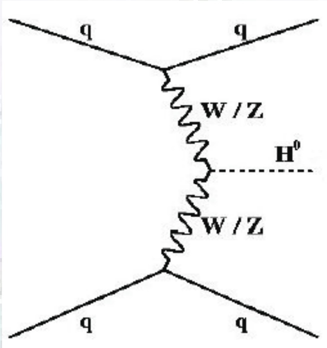
Impact of kinematical variables not shown in this plot

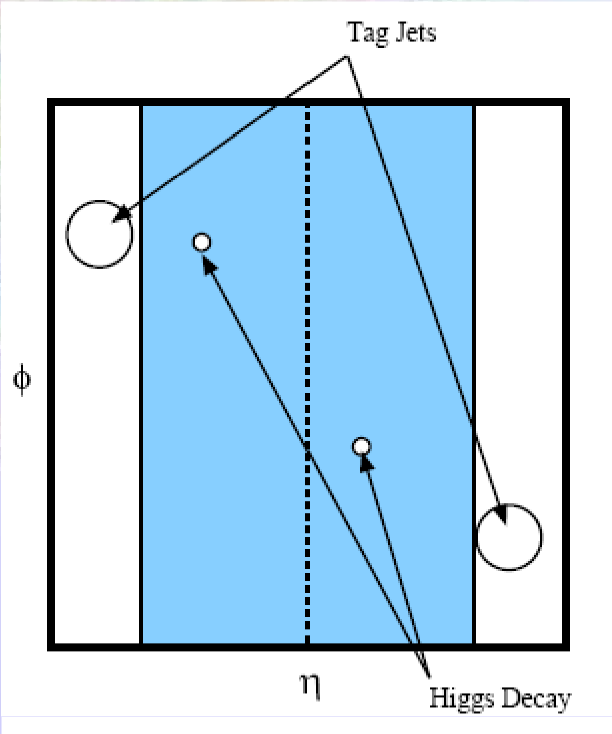
SM Higgs search VBF with H→ ττ and H→ WW

- At low Higgs masses the largest sensitivity search channels are found in the vector boson fusion production mode

- The two jet of the quarks are energetic and distributed in the forward region

- The Higgs decay products in between





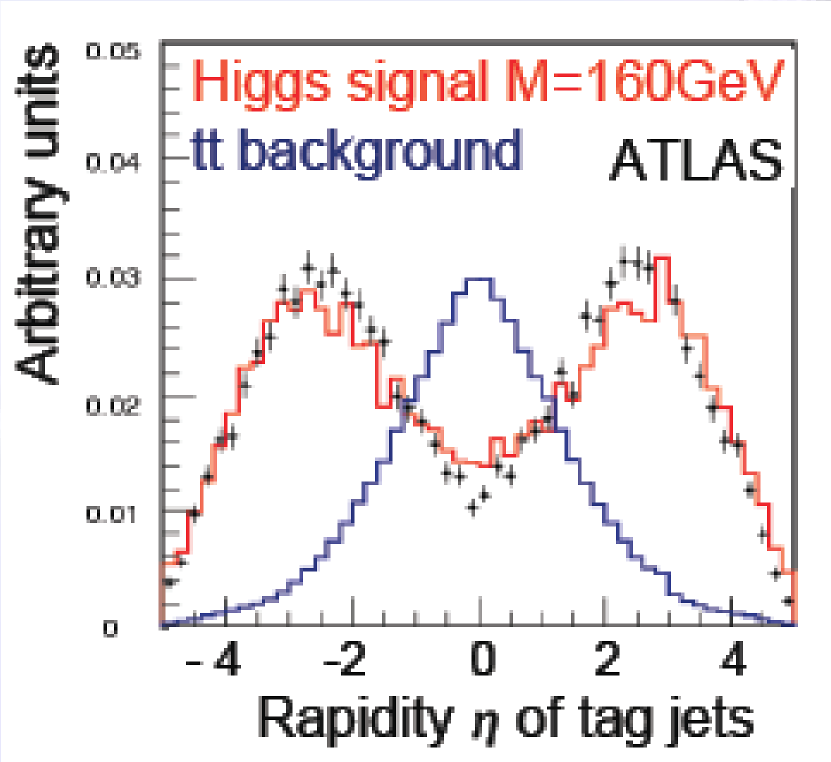
Signature:
two tag jets in the forward region
One of the W or τ decay leptonicaly

Irreducible Background
qq Z/W
Reducible backgrounds
QCD multi-jet, W+jet, Z+jet, g+jet and tt

SM Higgs search VBF with H→ ττ and H→ WW

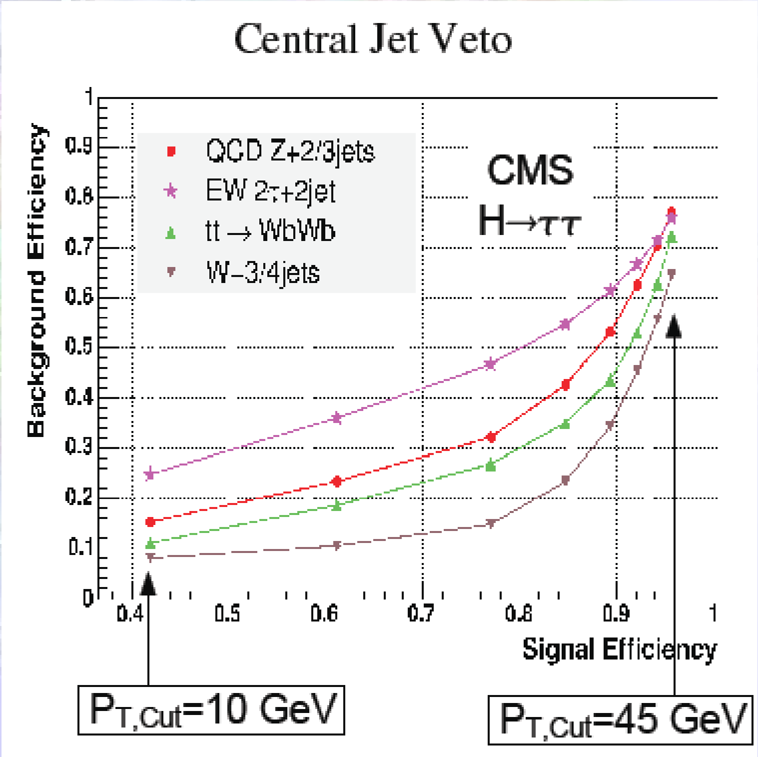
Significant background suppression by

Two tag jets in forward region



sn-atlas-2003-024

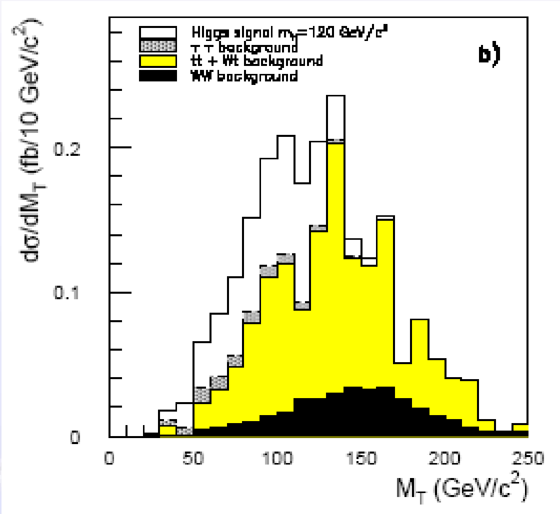
No Jet in central region



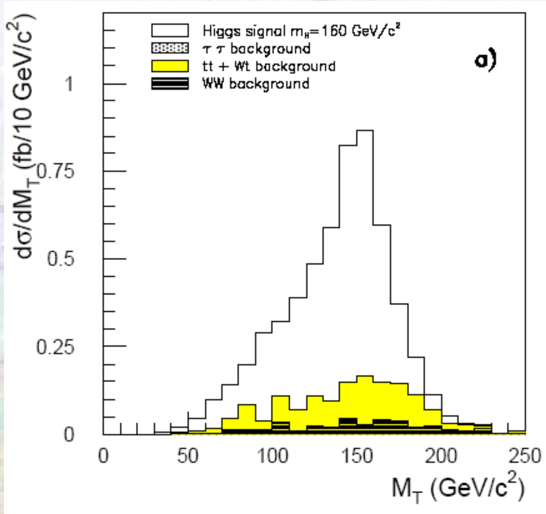
SM Higgs search VBF with H→ WW

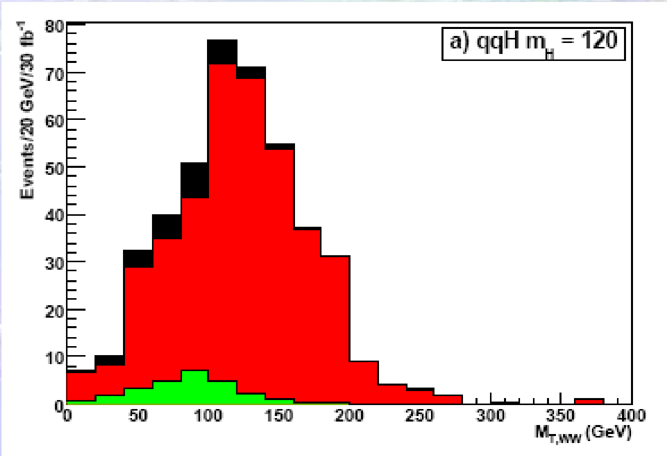
m_H=120 GeV

m_H=160 GeV

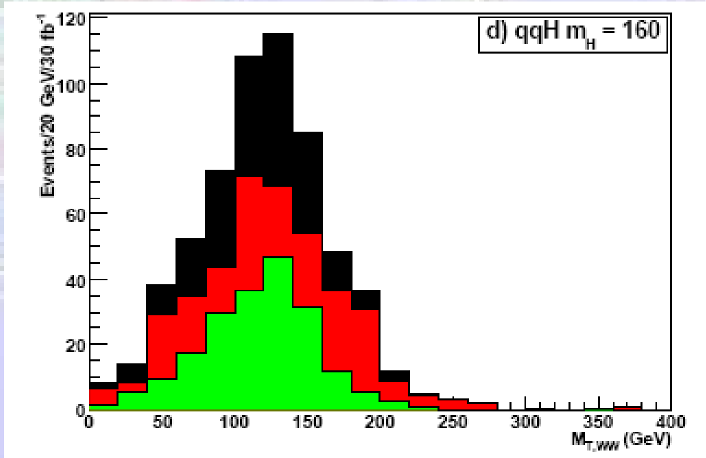


ATLAS





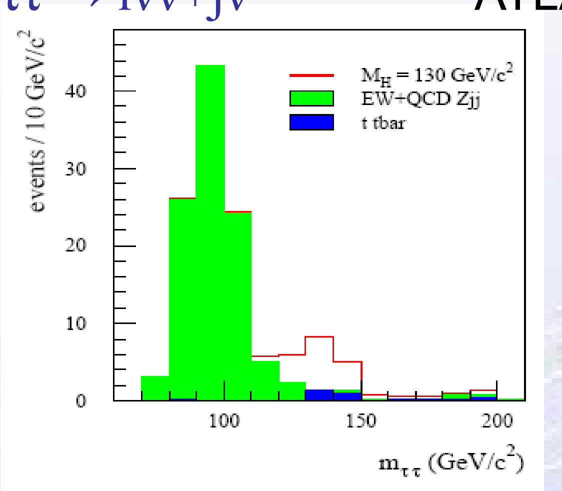
CMS

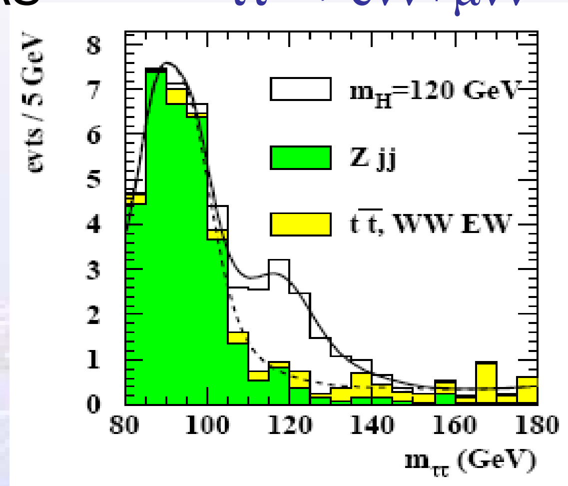


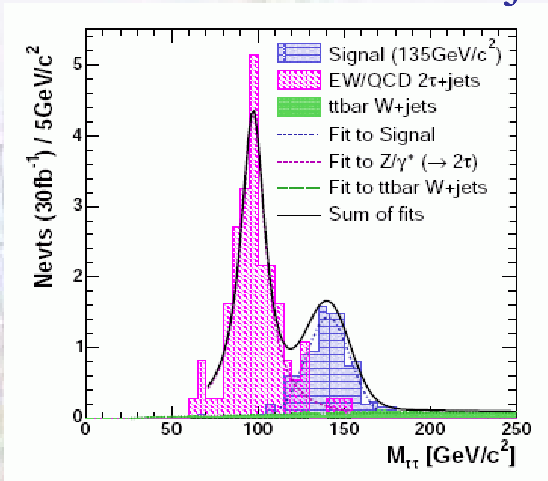
Signal to background with VBF increases by a factor >3

SM Higgs search VBF with H→ ττ

ττ → lνν+jν ATLAS ττ → eνν+μνν CMS ττ → lνν+jν







Backgrounds :

QCD ττ +jets, EW ττ +jets, W+jets, tt

Selection:

VBF tag jets

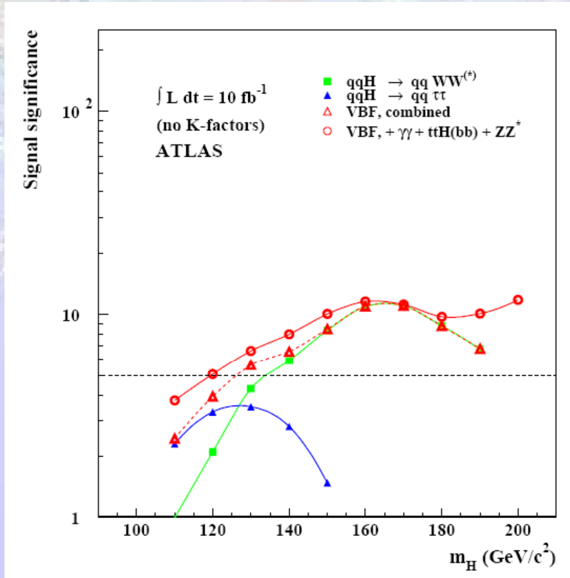
τ selection

MET reconstruction, Kinematical cuts

Background Control

Side bands

Relaxed cuts



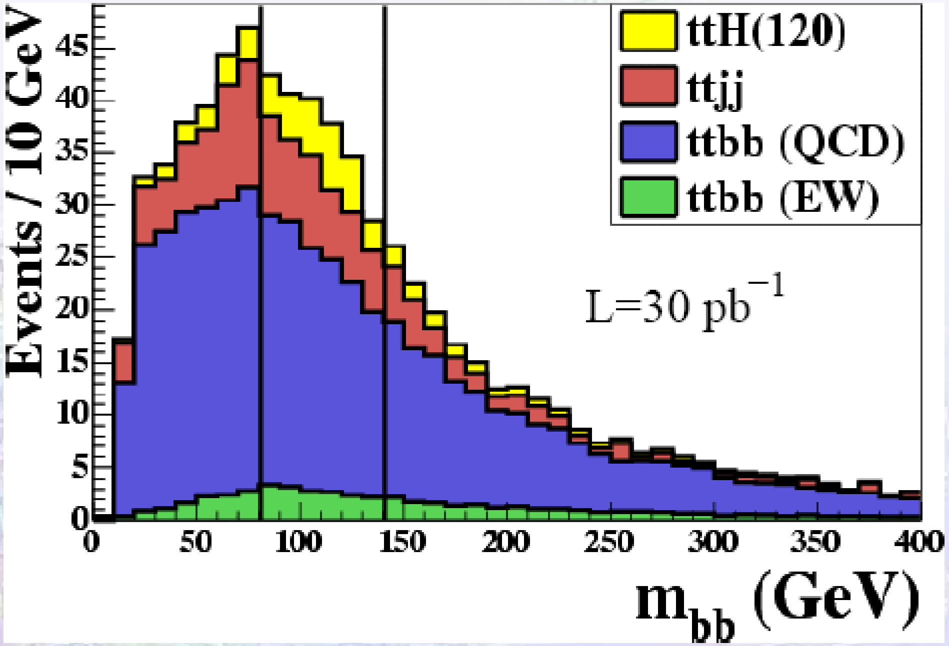
SM Higgs search ttH (H→ bb) →lvbbbbjj

Signature
4b-jets + lepton + 2 jets +MET

Irreducible background:
Non resonant ttbb

Reducible backgrounds:
ttZ, ttjj, WWjj

Event Selection:
Reconstruction of at least 6 jets
B-tagging of exactly 4 jets
Kinematical cuts
Invariant Mass of bb from H
Use of Likelihood functions
- To associate bs from t decays
- To discriminate ttbb bkg

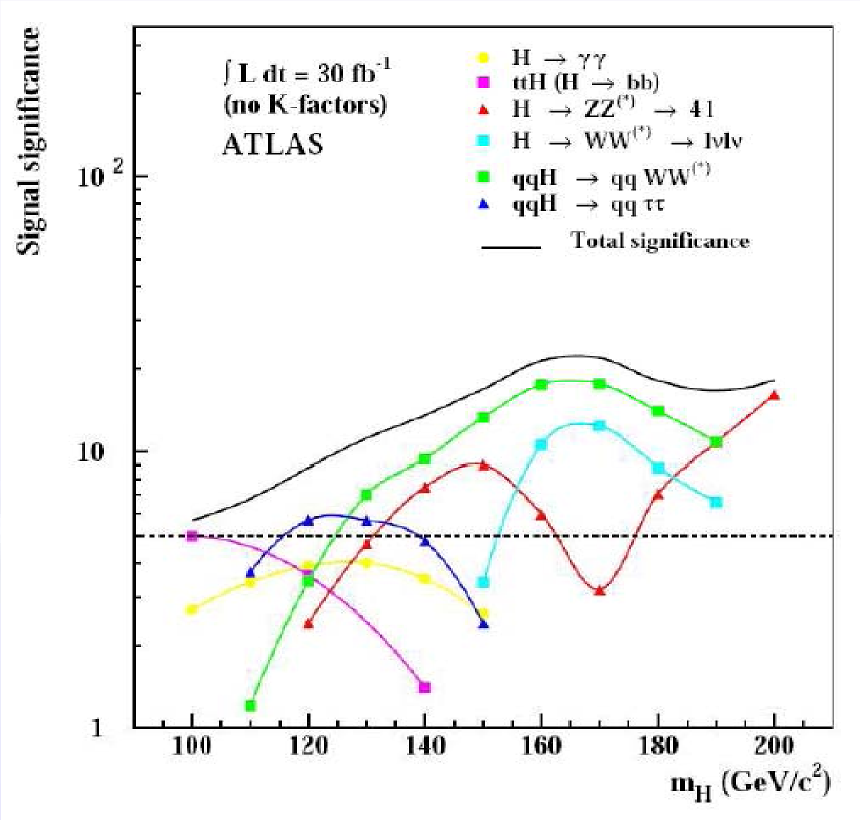


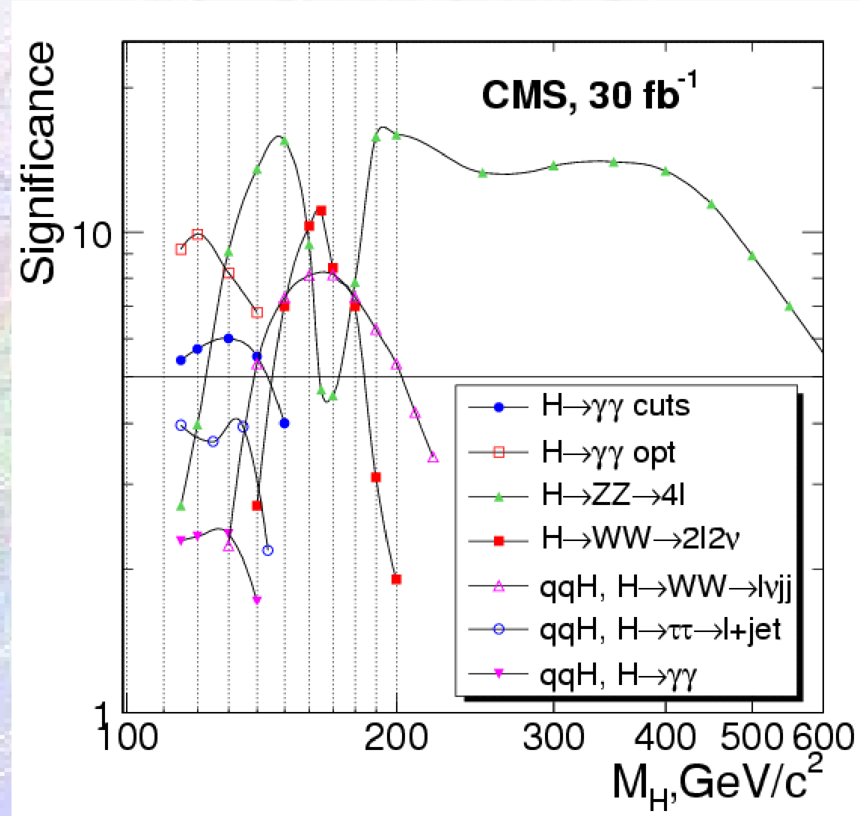
m_H = 120 GeV, L = 30 fb^{-1}
$S/\sqrt{B}$ = 2.8, with **LO**

Very challenging channel
Significant for very low Higgs masses

Difficult to control the background with the use of the data

LHC Summary for the discovery of the SM Higgs

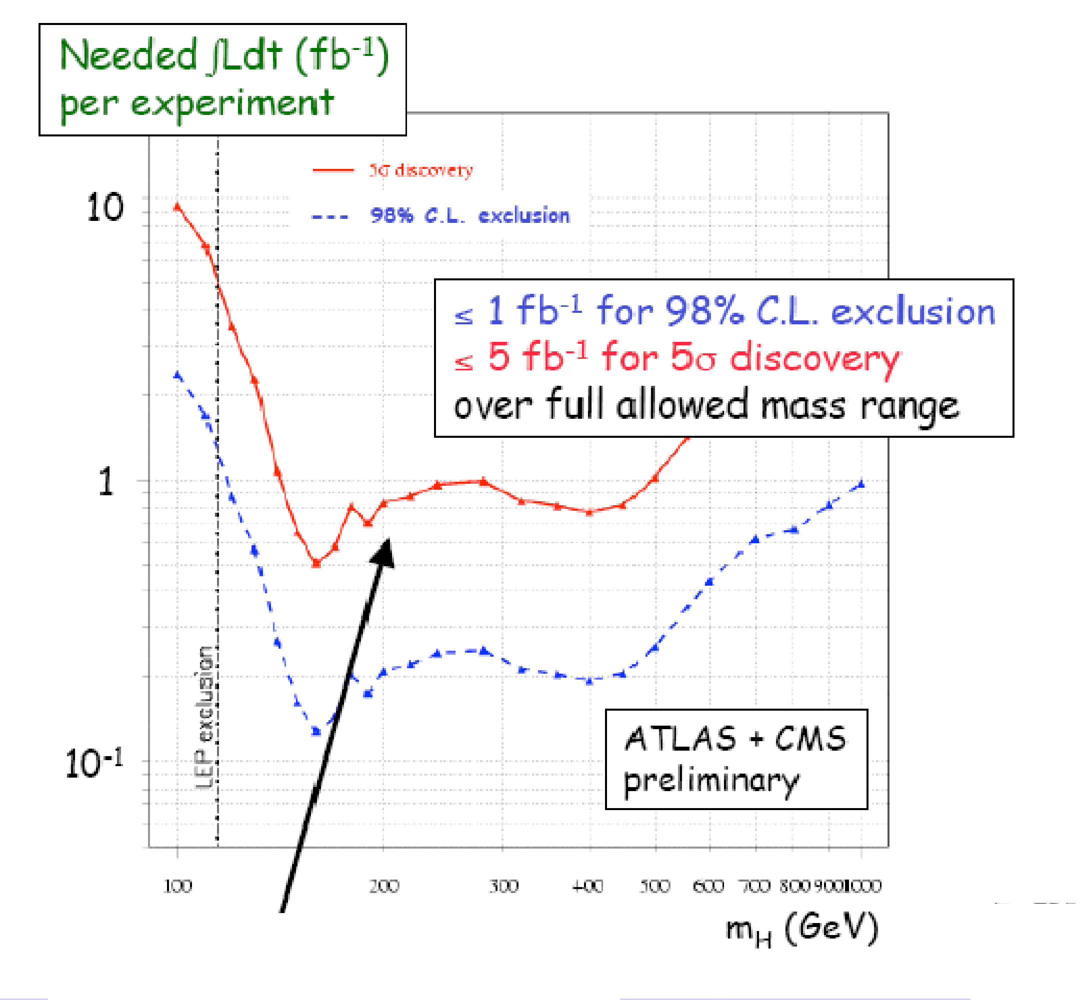




<u>ATLAS uses LO in the plot, while CMS uses NLO cross sections</u>

ATLAS new sensitivity study is ongoing

LHC Summary for the discovery of the SM Higgs



F.Gianotti, ICHEP06

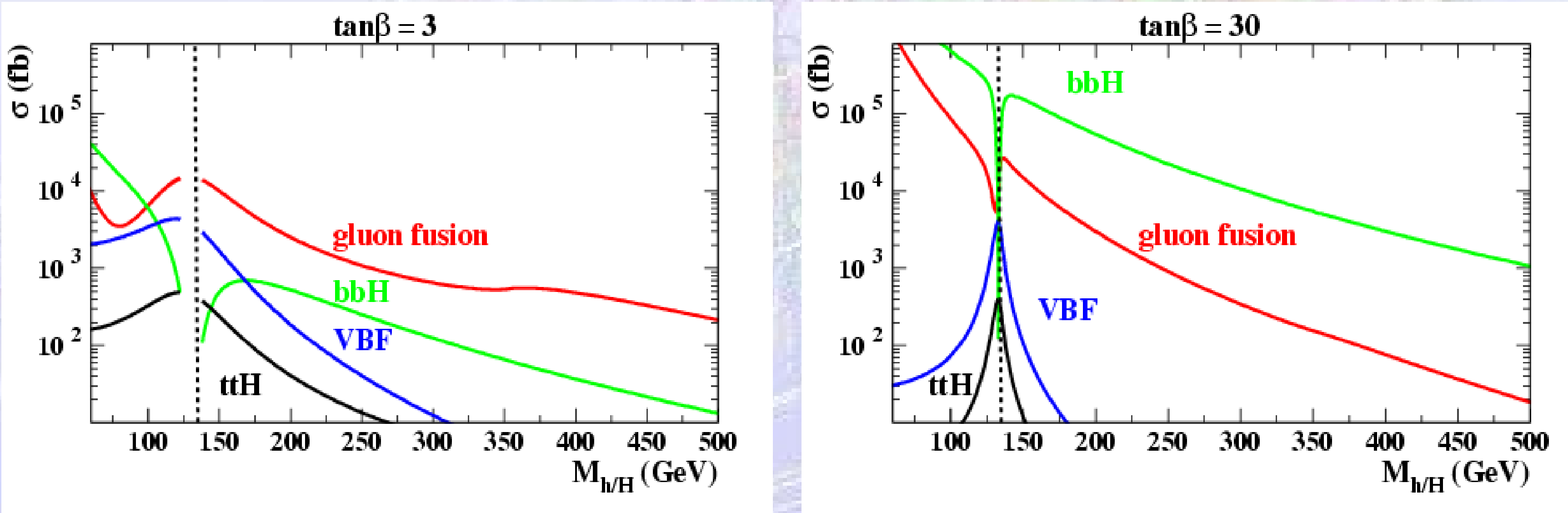
- 5σ discovery over all allowed mass range with ≤ 5 fb^{-1}

- More than one channels must be combined for early discovery at low masses (~ 115 GeV)

Production of the MSSM Higgs

- Higgs sector of the MSSM: physical states h,H,A,$H^{\pm}$
- Described by two parameters at lowest order: M_A, tanb
- **Discovery of extended Higgs sector leads to physics beyond SM**

tanb = 3 **MSSM neutral Higgs production** **tanb=30**

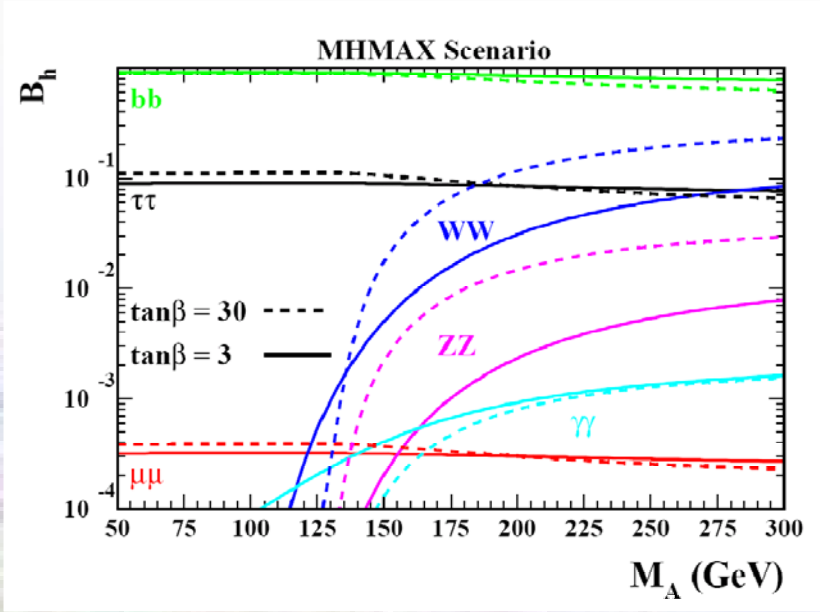


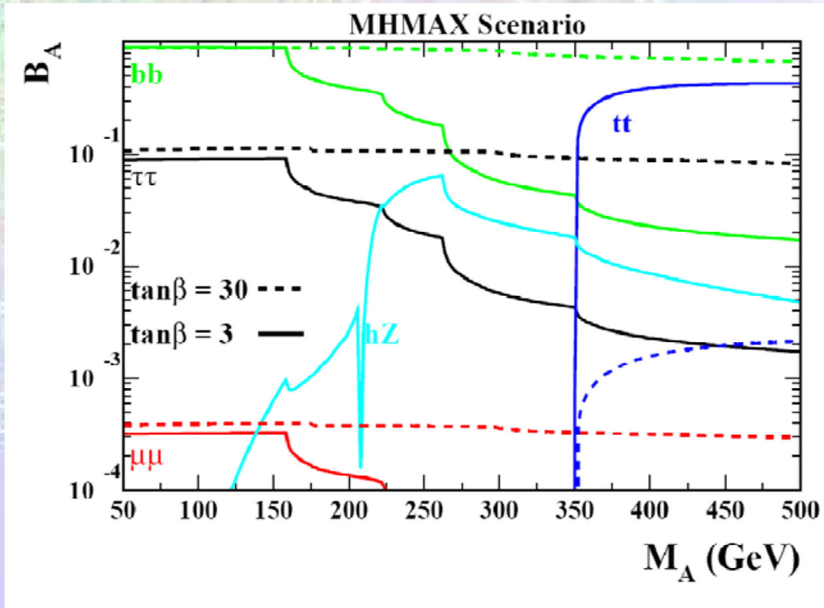
At high tanb associated production bbH is greatly enhanced

MSSM Higgs search

Channels taken into consideration

Search channel	Mass range
$VBF : H \to \tau\tau$	110 GeV to 180 GeV
$VBF : H \to WW$	110 GeV to 250 GeV
$VBF : H \to \gamma\gamma$	110 GeV to 180 GeV
$ttH, H \to bb$	110 GeV to 150 GeV
$GGF/bbh, H \to \mu\mu$	70 to 1000 GeV
$GGF/bbh, H \to \tau\tau \to lep.had.$	110 to 1000 GeV
$GGF/bbh, H \to \tau\tau \to had.had.$	450 to 1000 GeV
$H \to ZZ \to \ell\ell\ell\ell$	100 GeV to 420 GeV
$GGF, H/A \to tt$	450 to 600 GeV
$H/A \to \gamma\gamma$	60 to 400 GeV
$WH \to \ell\nu bb$	70 to 130 GeV
$GGF : H \to WW \to \ell\nu\ell\nu$	140 to 200 GeV
$WH \to \ell\nu WW \to \ell\nu\ell\nu\ell\nu$	140 to 200 GeV
$GGF : H \to hh \to \gamma\gamma bb$	100 360, 40 to 130 GeV
$GGF : A \to Zh \to \ell\ell bb$	100 360, 40 to 130 GeV
$tt \to H^{\pm}bWb \to \tau\nu\ell\nu b$	70 to 170 GeV
$tt \to H^{\pm}bWb \to \tau\nu bqqb$	70 to 170 GeV
$gb \to H^{\pm}t : H^{\pm} \to \tau\nu, tb$	180 t0 1000 GeV





…and BR to WW,ZZ strongly suppressed

MSSM Higgs search bbH (H→ ττ)

Signature

ττ (≥1 decaying to l) bb

Irreducible background:

ττ bb

Reducible backgrounds:

Z+jets, tt, bb,Wt,WW,WZ

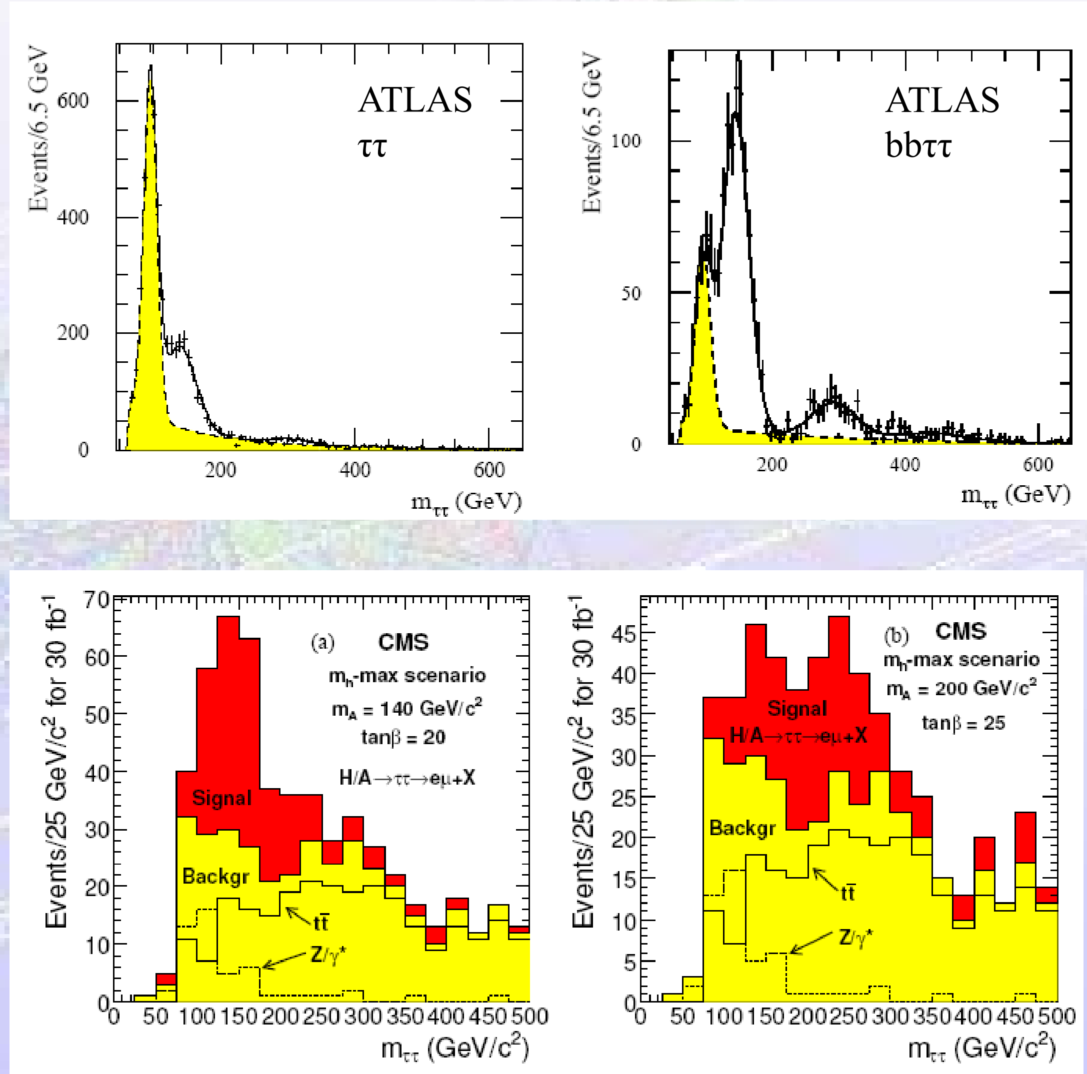
Event Selection:

pair of τ

b-tagging of ≥ 1jet

central jet veto

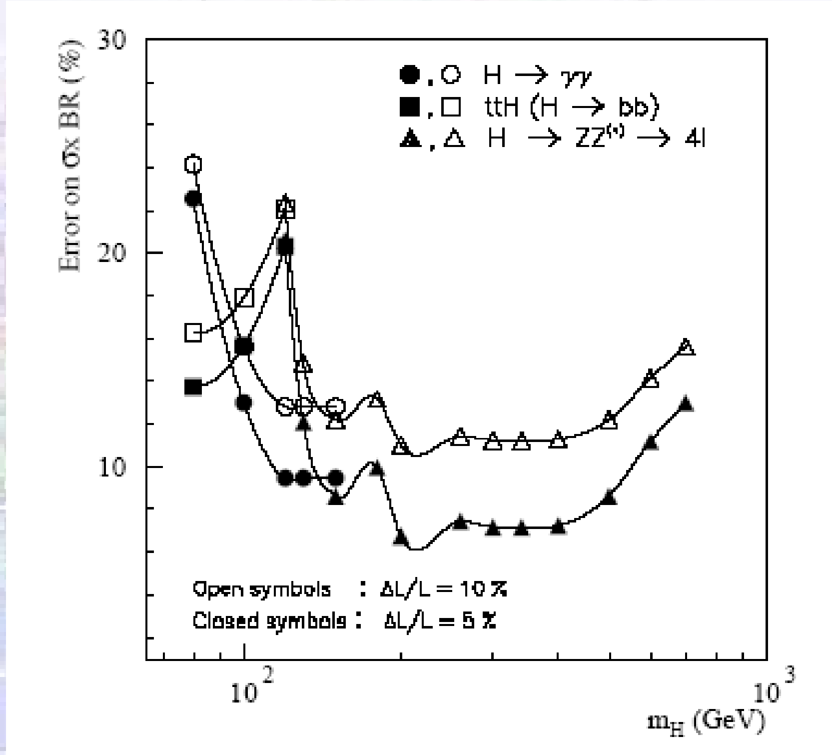
MET reconstruction



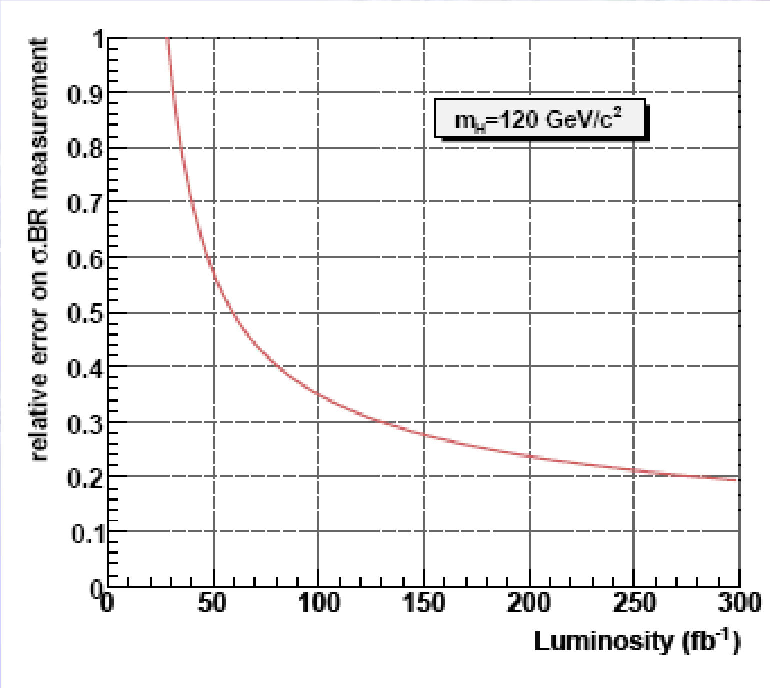
Higgs Parameters – Branching ratios

Luminosity control
Detector systematics
Background control from data

ATLAS 300fb^{-1}



CMS WH,ZH (H→ γγ)



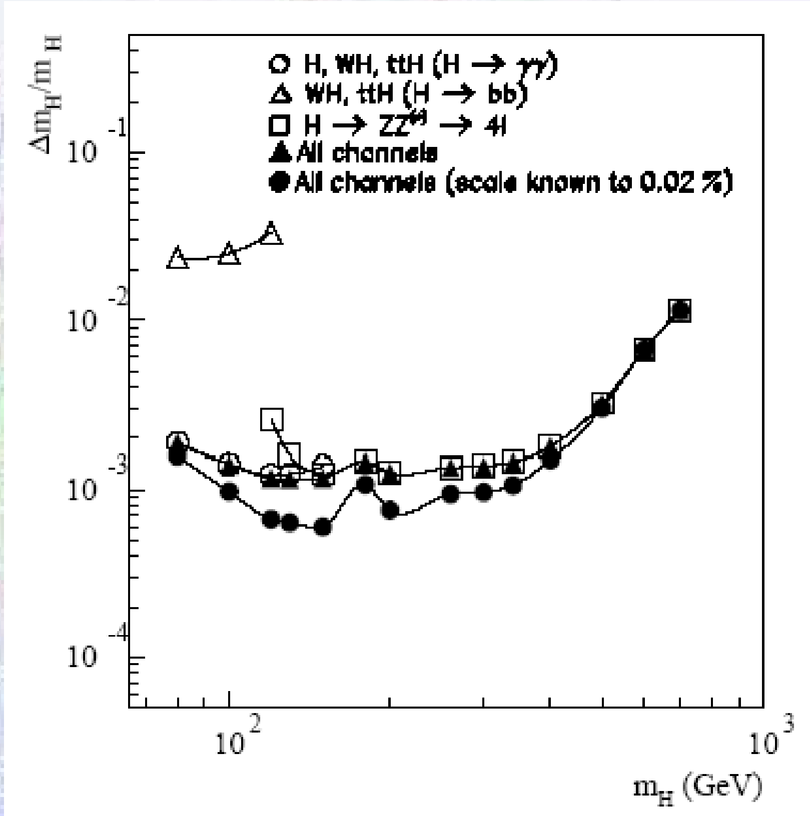
Higgs Parameters - Mass Determination

Channels with complete reconstruction of Higgs decay products

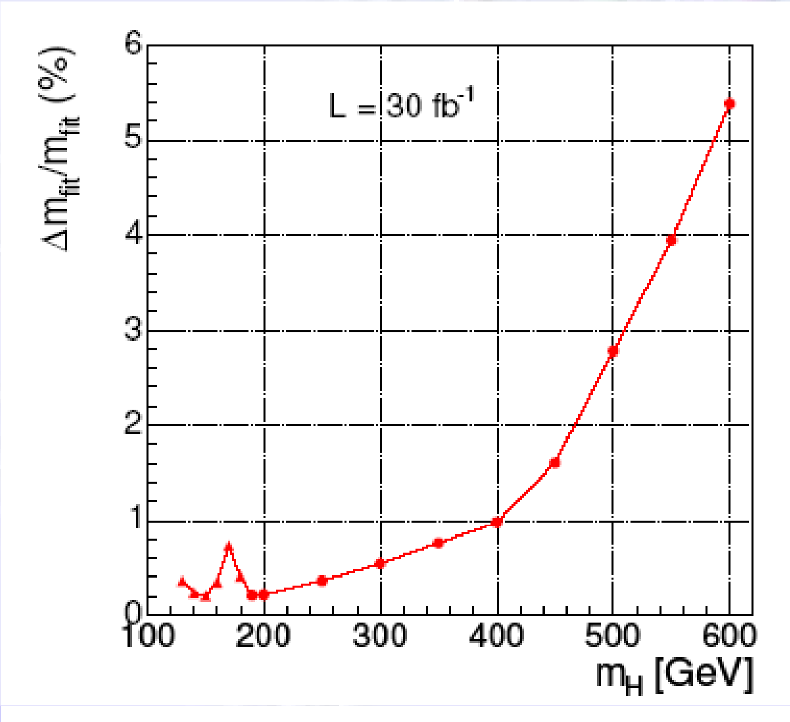
$H \rightarrow 4$ leptons

$H \rightarrow \gamma\gamma$

ATLAS 300fb^{-1}



CMS H→4l 30 fb^{-1}



Conclusions

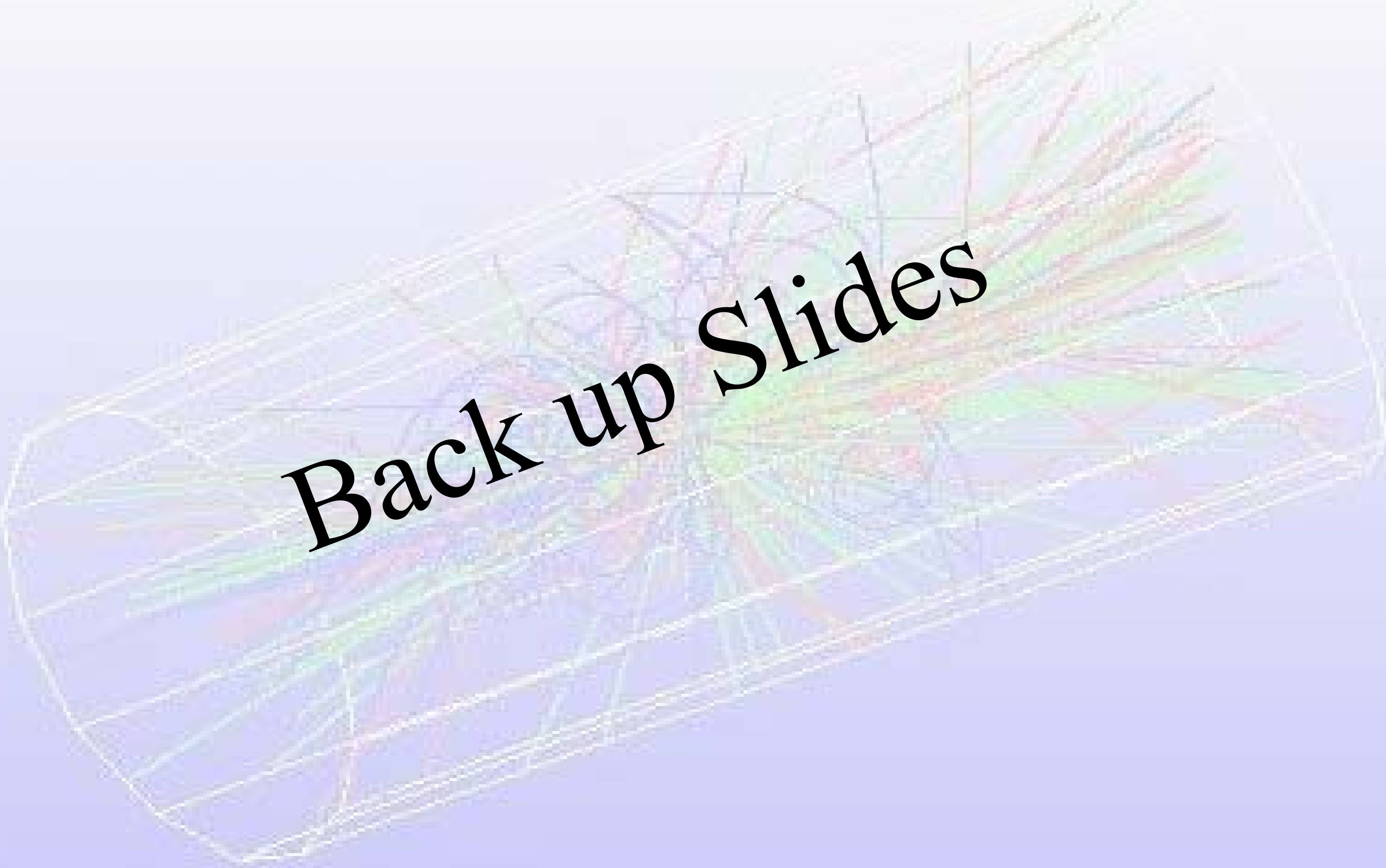
- If the standard model Higgs boson exist, it cannot escape detection at the LHC.

- Discovering the Higgs boson is just the first step, the next step is to measure its mass and couplings.

- Discovery of enhanced Higgs sector directly prompts to physics beyond the SM.

… the adventure is about to start

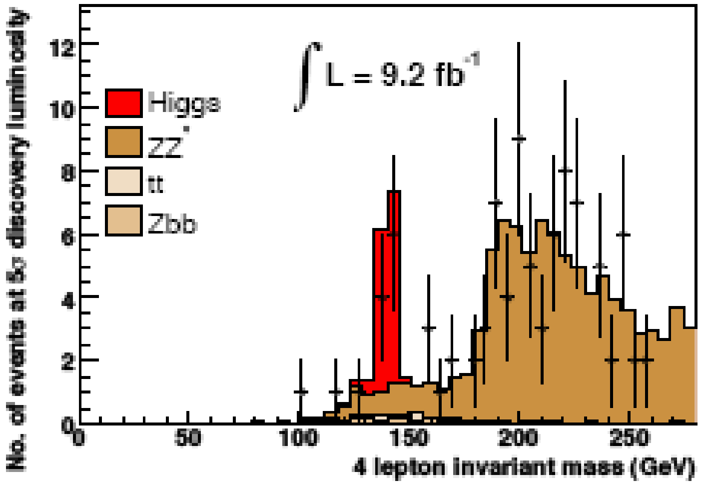
Back up Slides

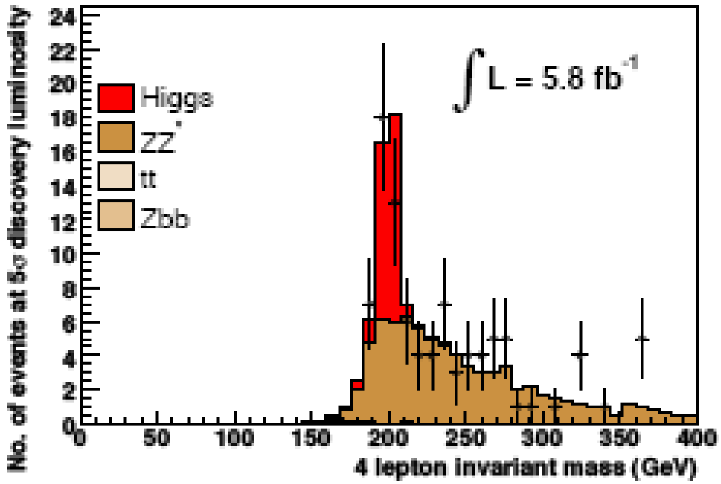


SM Higgs Search $H \rightarrow ZZ(ZZ^*) \rightarrow l^+l^-l^+l^-$

Number of expected events for 5σ discovery

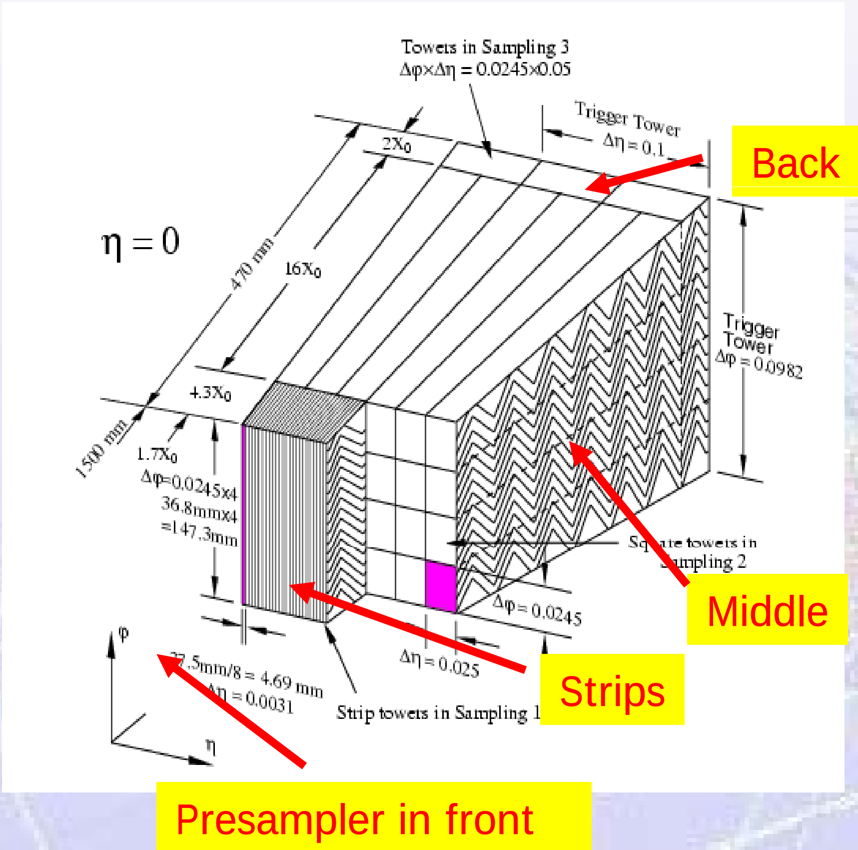
CMS





	Signal	$t\bar{t}$	Zbb	ZZ^*/γ^*
Production cross-section (NLO)	17.9×10^3	840×10^3	555×10^3	28.9×10^3
$\sigma\times$BR(4 lepton final state)	23.8	-	-	367.5
Pre-selection: $\sigma\times\text{BR}\times\epsilon$	7.39±0.09	743±2	390±1	37.0±0.4
Level-1 trigger	7.36±0.09	707±2	360±1	36.3±0.4
High Level trigger	6.82±0.08	282±1	237±1	32.5±0.4
$e^+e^-\mu^+\mu^-$ reconstructed	5.51±0.07	130±1	141±1	24.1±0.3
Vertex and impact parameter cuts	5.03±0.07	18.9±0.3	18.4±0.2	21.5±0.3
Isolation cuts	4.92±0.07	5.1±0.1	12.3±0.2	21.3±0.3
Lepton p_T cuts	4.78±0.07	1.93±0.09	1.78±0.06	18.7±0.3
Z mass window cuts	4.45±0.07	0.15±0.03	0.12±0.02	14.4±0.3
Higgs mass window cuts	3.64±0.06	0.006±0.005	0.006±0.003	1.61±0.09
Expected events for $\int\mathcal{L} = 10\ \text{fb}^{-1}$	36.4±0.6	0.06±0.05	0.06±0.03	16.1±0.9

SM Higgs Search H→ γγ



γ candidate

↓

LVL1 EM25i (EM30i) 2EM15i (2EM20i)

↓

Cut on HAD leakage, 2^{nd} sampling of EM

Rejects jets with high energy pions and wide showers

↓

Cuts on 1^{st} sampling of EM calo

Rejects jets with one or more p^0, h,…

↓

Isolation cuts (ID or EM calo)

Rejects low multiplicity p^0 jets

↓

Photons direction corrected for PV

Low luminosity:

η from strips and middle calorimeter

Z_v measure from ID (σz=40 μm)

High luminosity:

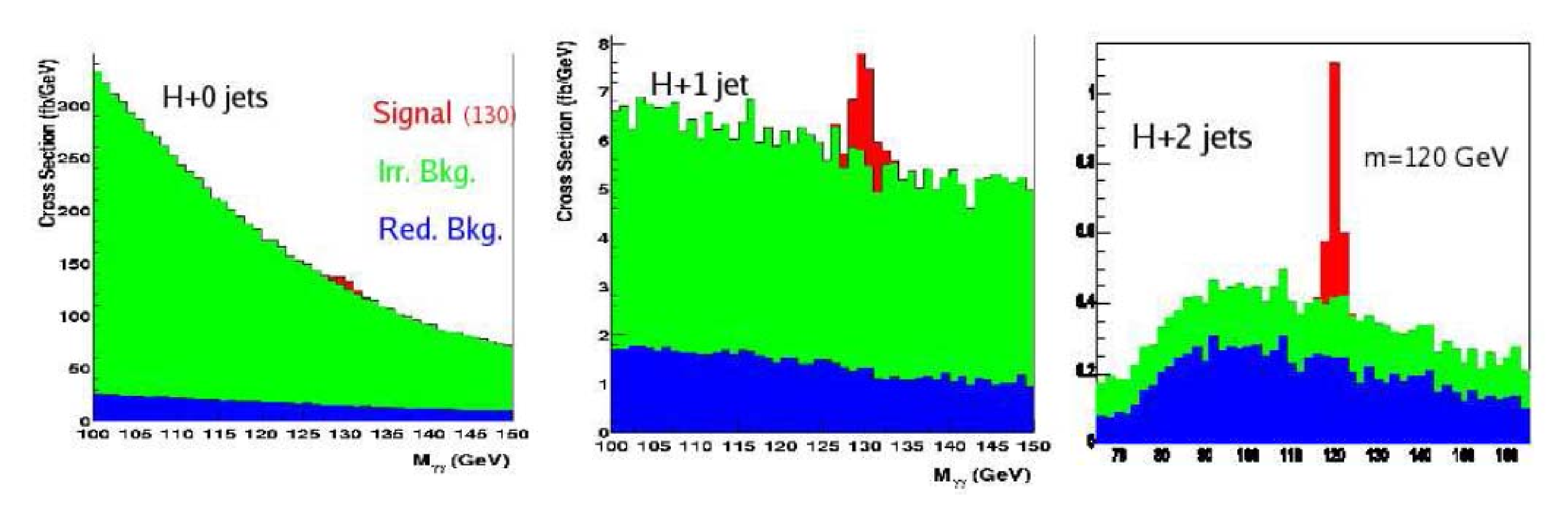
Photons direction obtained with calorimeter information only

crucial role for fine η segmented strips

SM Higgs Search H→ γγ + n jets

H + 0 jets from gg -> H.
H + 1 jet at NLO, plus VBF production with one lost jet.
H + 2 jets from VBF.

ATLAS preliminary



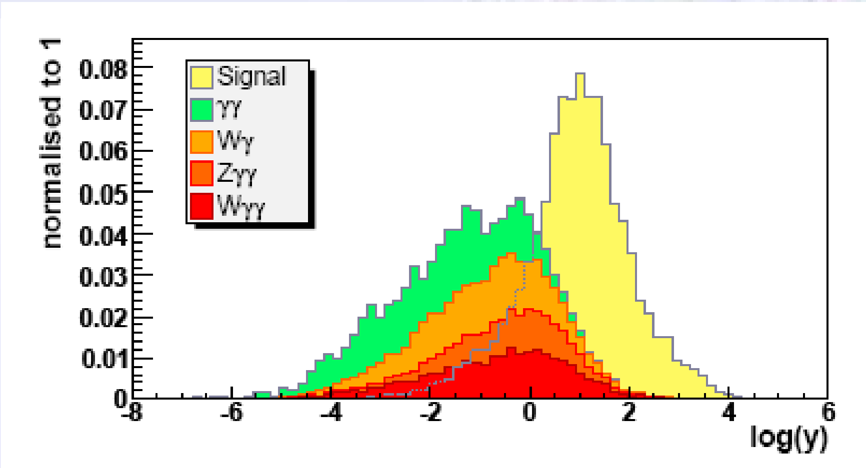
With the use of different jet configurations

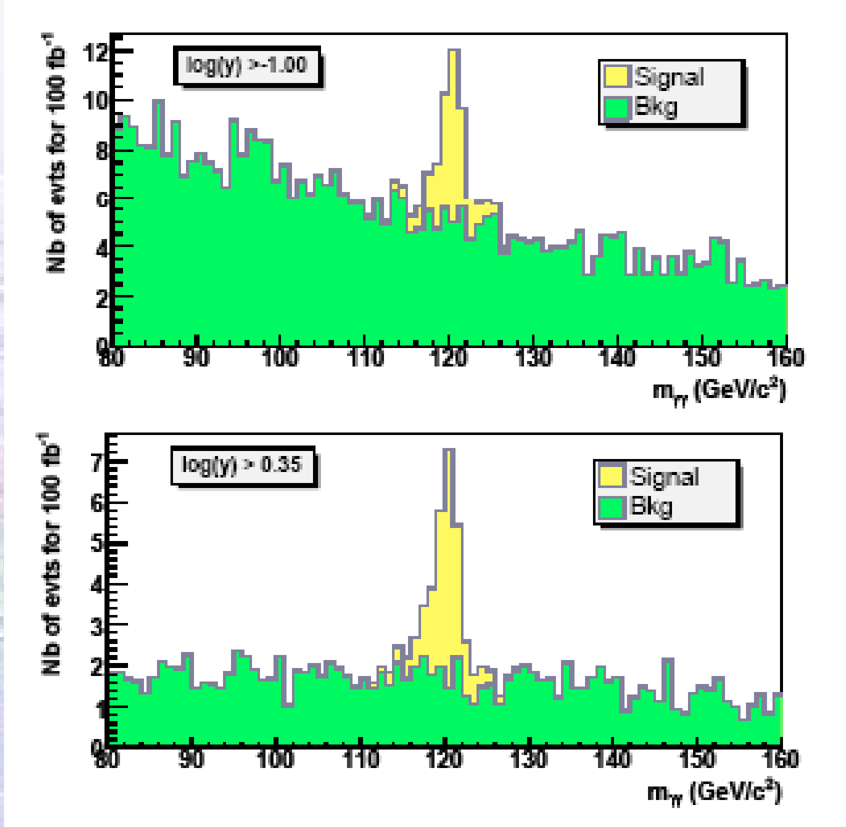
- the signal is decreased
- but the $S/\sqrt{B}$ is increased

SM Higgs Search W(Z)H (H→ γγ)

CMS

Variables used in likelihood analysis of CMS
- transverse energy of the photons and of the lepton
- the ΔR distances between lepton and each photon
- the missing transverse energy
- the angle between the directions of the missing transverse energy and of the highest E_T photon.





Significance for 100 fb^{-1}

m_H (GeV/c^2)	working point $log(y) >$	significance	WH	ZH	$W\gamma\gamma$	$Z\gamma\gamma$	$W\gamma$	$\gamma\gamma$	γ-jet	$t\bar{t}$	$b\bar{b}$
115	0.41	4.30 σ	22.1	1.8	49.3	30.9	33.0	10.2	1.7	0.16	10×10^{-5}
120	0.35	4.09 σ	20.7	1.6	51.2	36.2	34.5	12.4	1.9	0.15	10×10^{-5}
130	0.68	3.64 σ	14.6	1.3	30.7	16.9	18.7	6.0	1.4	0.10	4×10^{-5}
140	0.99	3.35 σ	11.4	1.0	18.9	10.3	10.6	3.7	1.0	0.04	1×10^{-5}
150	0.83	2.87 σ	10.4	0.9	20.2	11.7	12.3	5.4	1.1	0.03	3×10^{-5}

MSSM Higgs search bbH (H→ μμ)

Small branching fraction, BR(H -> μμ) ~ 10^{-4} but good mass resolution, ~ 1-2 %

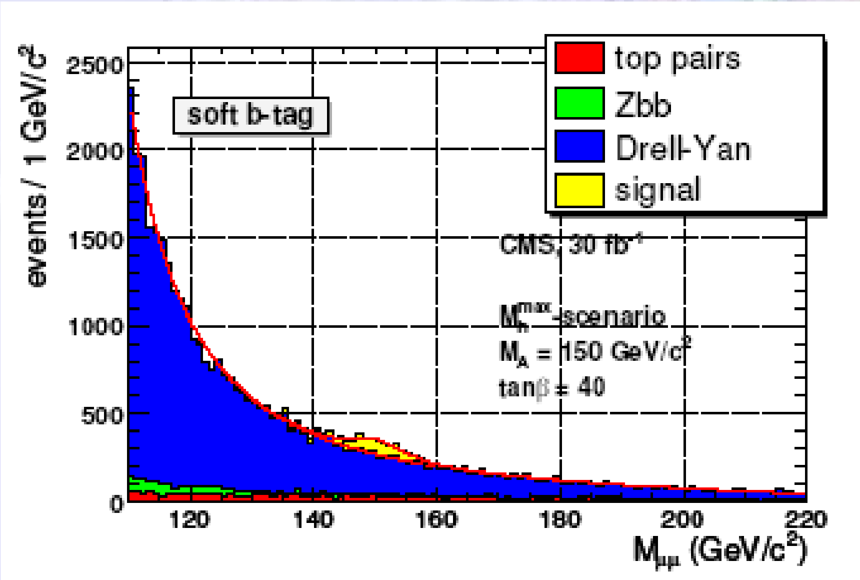
Irreducible bkg: bbμμ

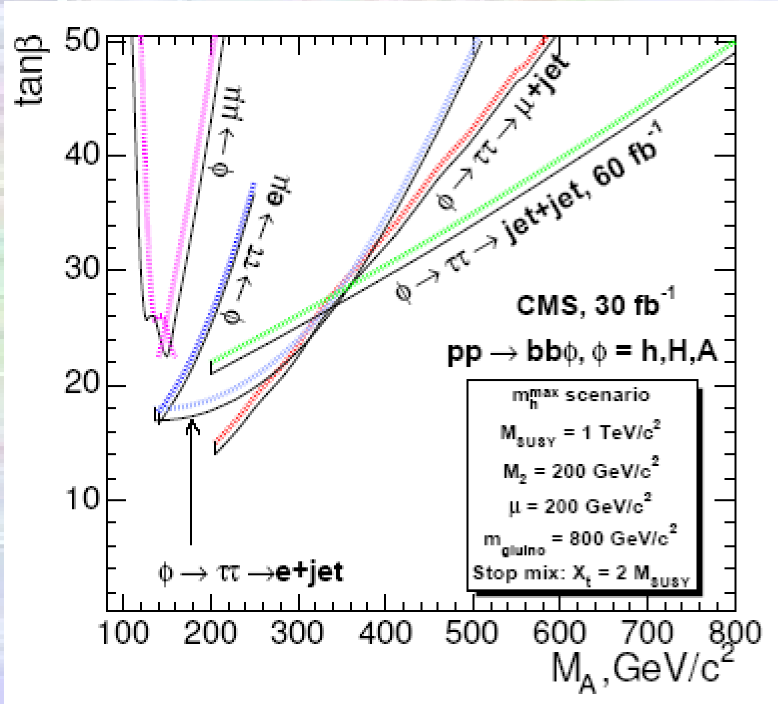
Reducible bkgs: Z->μμ, tt

Event Selection

b tagging

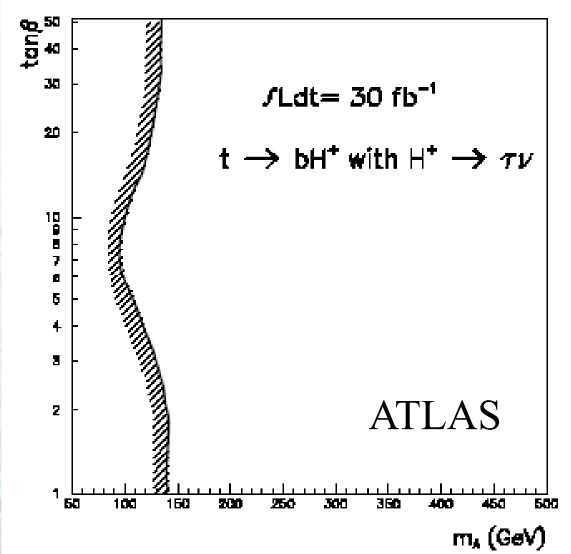
isolation, MET, jet veto



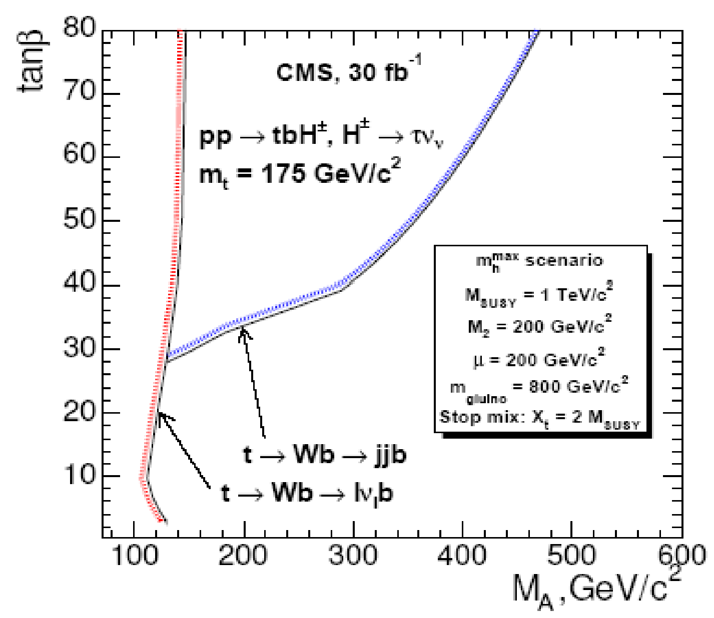


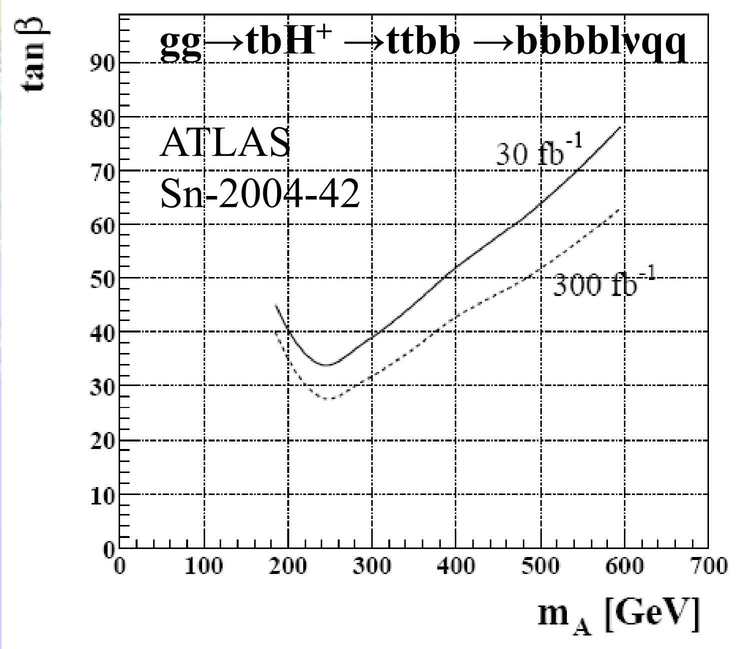
MSSM Higgs search tbH^+ $(H\to \tau\nu)$

$t \to bH^+ \to b\tau\nu$
$pp \to tbH^+ \to wb\tau\nu \to jjbb\tau\nu$
$pp \to tbH^+ \to wb\tau\nu \to l\nu bb\tau\nu$
$pp \to tbH^+ \to ttbb \to bbbbl\nu qq$

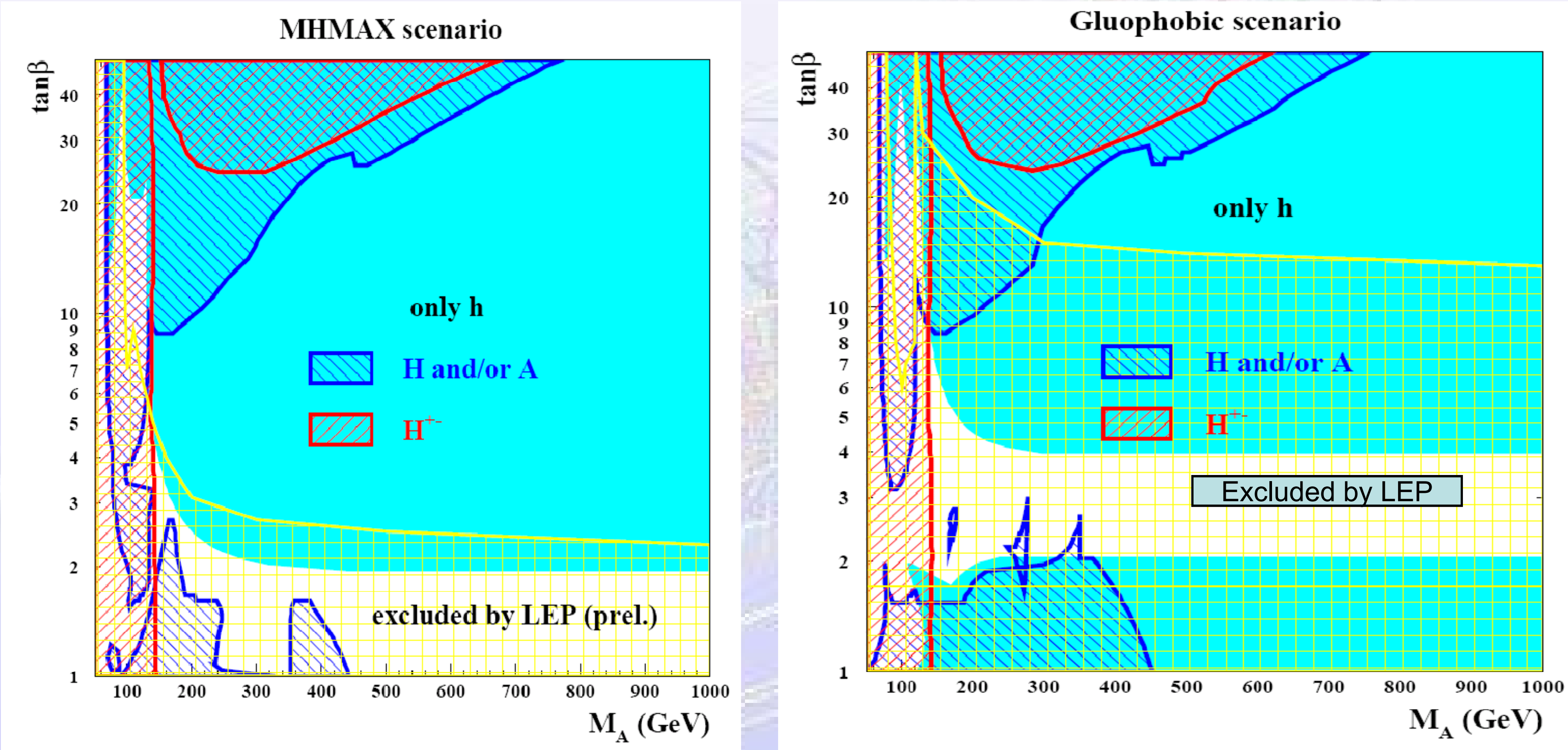


CMS





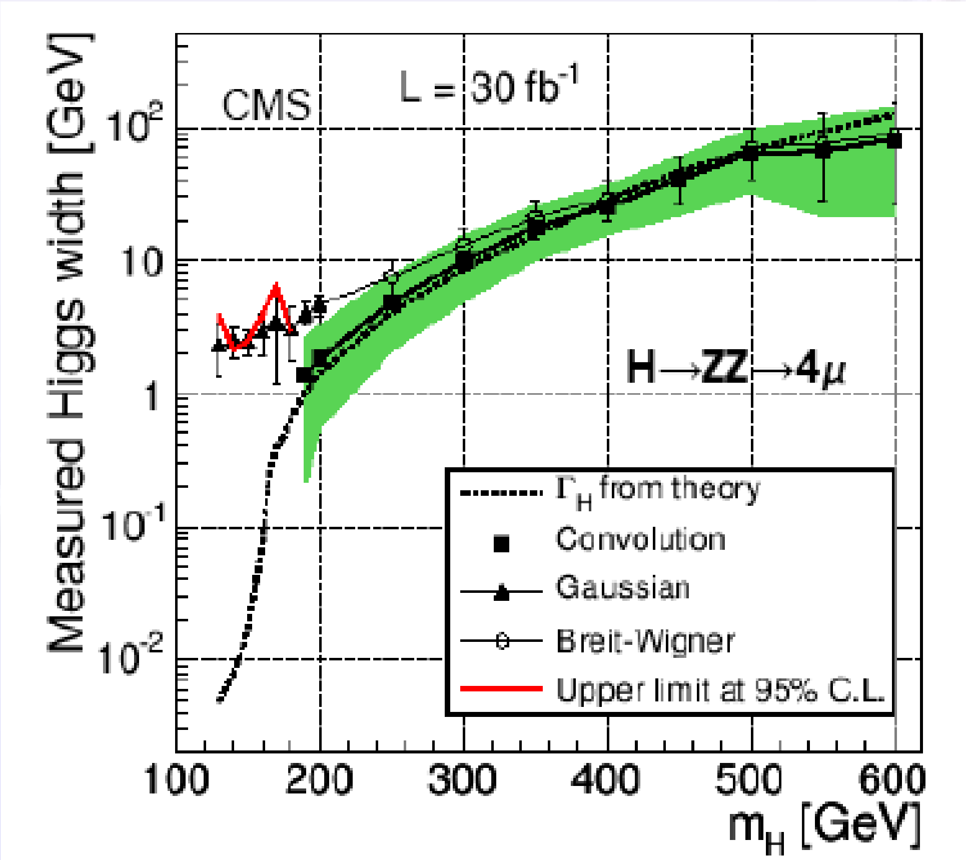
MSSM Higgs search – Overall sensitivity

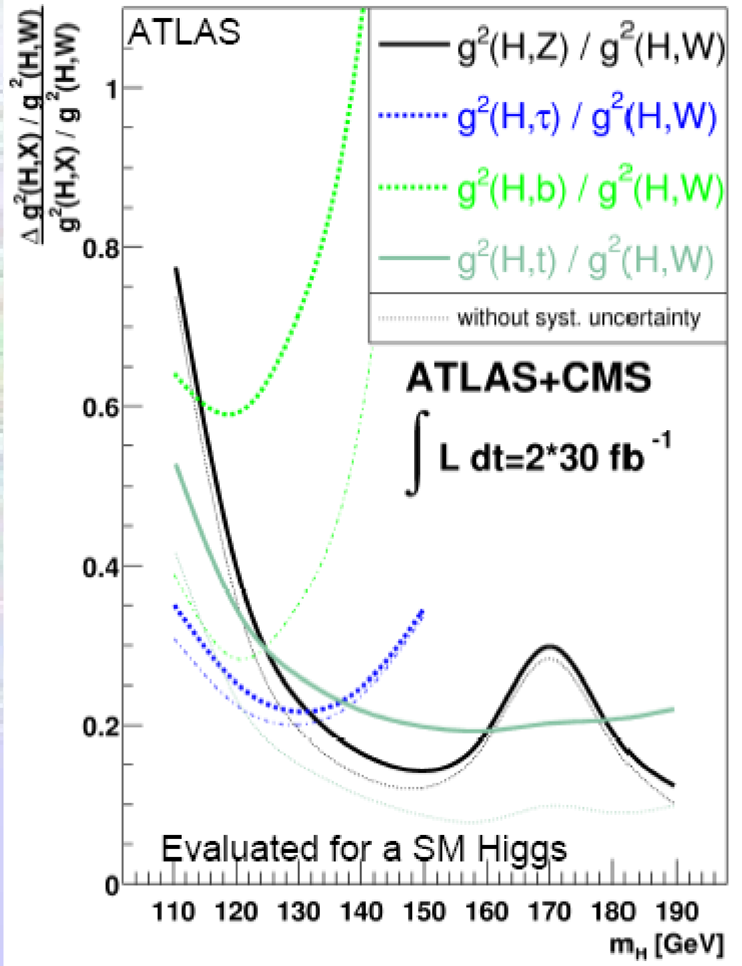


Higgs Parameters – Width

Detector resolutions are of the order of 1 GeV

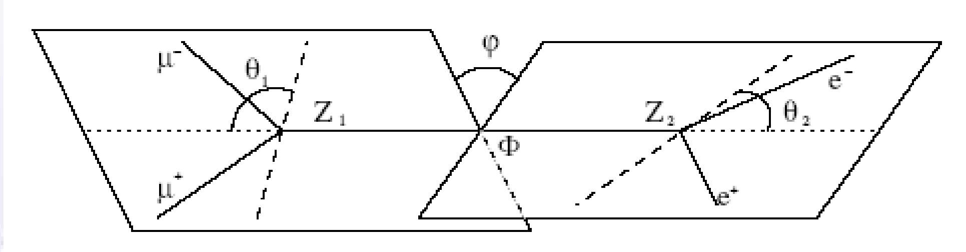
Can't measure the width of a SM Higgs Boson directly for m_H<200 GeV



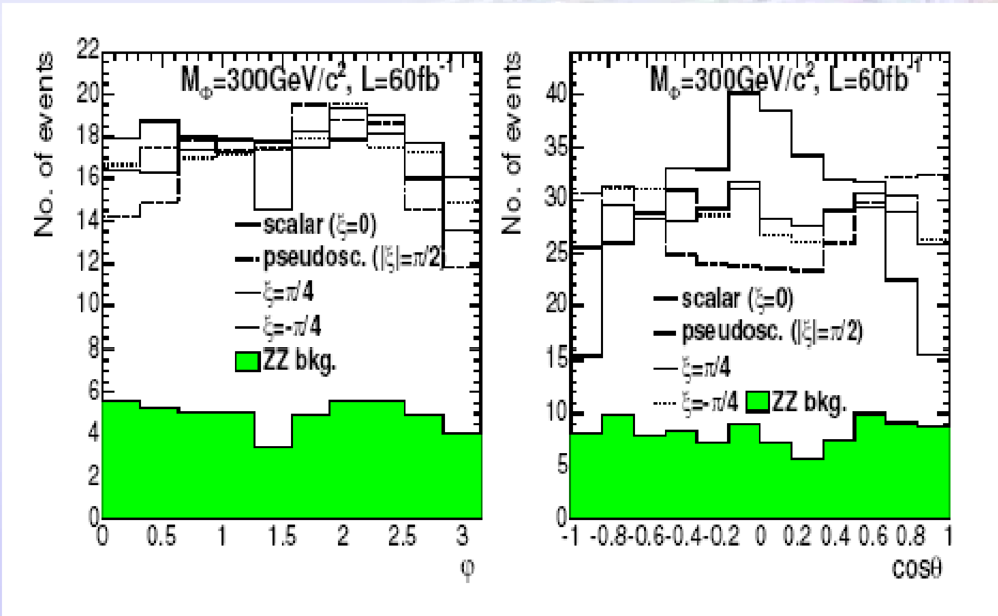


Higgs Parameters – spin, CP

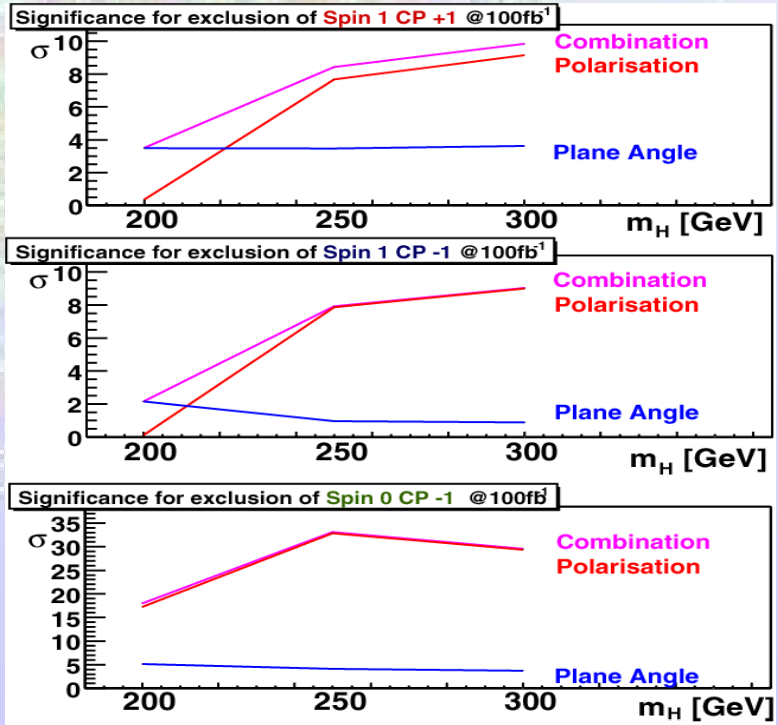
H->4 leptons
φ: Z decay planes angle
θ: Z polarization



CMS



Atlas-sn-2003-025

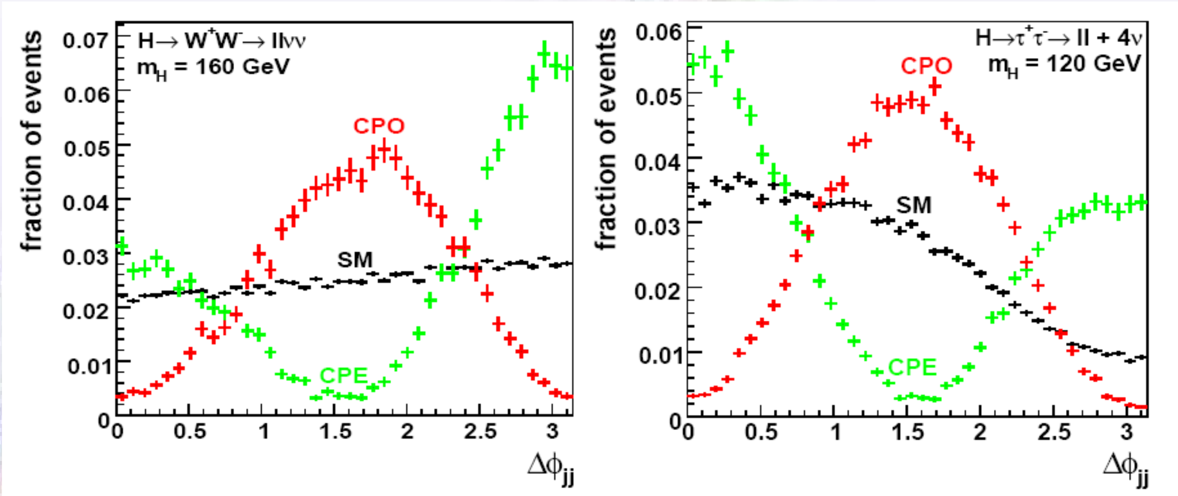


Higgs Parameters – Couplings to Weak Bosons

sn-atlas-2007-060

VBF H->WW, H->ττ

$\Delta\varphi_{jj}$: azimuthal angle of tag jets



Determination of the dominant coupling term

integrated luminosity, hypothesis tested		probability for $> 5\sigma$	$< 5\,\%$
$H \to W^+W^- \to l l \nu\nu$			
$10\,\mathrm{fb}^{-1}$	CPE	59 %	100 %
	CPO	35 %	98 %
$30\,\mathrm{fb}^{-1}$	CPE	100 %	100 %
	CPO	100 %	100 %
$H \to \tau^+\tau^-$ combined			
$30\,\mathrm{fb}^{-1}$	CPE	2 %	68 %
	CPO	0 %	52 %

Put limits on anomalous couplings